

**ELECTROPHYSIOLOGICAL INDICES OF  
RESPONSE INHIBITION IN THE STOP-SIGNAL TASK**

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**by**

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## **CERTIFICATION**

I, Aneta Dimoska, declare that this thesis, submitted in fulfillment of the requirements for the award of Doctor of Philosophy, in the Department of Psychology, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualification at any other academic institution.

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Aneta Dimoska

13 May 2005

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## **Abstract**

Response inhibition is vital for the performance of everyday tasks, allowing us to stop and adjust inappropriate behaviour in accord with our external environment and our own internal directions, while a deficiency in this process is believed to lead to impulsive behaviours. The main aim of this thesis was to investigate the nature of response inhibition in adults using the stop-signal task, a laboratory paradigm which allows estimation of the latency of the unobservable inhibitory response. This was achieved through: (a) a comparison of inhibition in the typical (simple) stop-signal task with other forms of inhibition, (b) a within-subject manipulation of stop-signal probability, and (c) an examination of response inhibition in populations characterised by impulsivity. Furthermore, throughout this thesis, event-related potentials (ERPs) were examined to provide an insight into the electrophysiological nature of response inhibition. Therefore, a secondary aim of this thesis was to further elucidate the functional significance of inhibition-related ERPs. The comparison of the simple stop-signal and go/nogo tasks revealed that inhibition manifests more centrally when an ongoing response is inhibited successfully, relative to the frontal distribution of inhibition when a response is merely in preparational stages, reflecting the differential sites of inhibitory control acting on response processing between the two tasks. However, when the stop-signal inhibitory response was manipulated by including an additional stimulus discrimination, creating a *stop/no-stop* (selective) form of inhibitory control, the latency of the inhibitory response and the manner in which responses were inhibited remained unaffected. Thus, inhibiting an ongoing response, whether it be in a simple or selective context, was associated with a fast, centrally-located inhibitory action. The electrophysiological index of this “urgent” stop-

signal inhibition process was found to be reflected in the P3 component on successful stop trials, while the small auditory N2 was believed to be associated with a frontally-located, deliberate form of response selection or control, a process which may be by-passed by subjects when a more urgent form of inhibitory control is required. The N2 and P3 for failed stop trials, however, were shown to be overlapped by response-related components reflecting erroneous processing. The manipulation of stimulus probabilities revealed that larger ERP component amplitudes for *rare* stop-signals may not necessarily reflect greater inhibitory activation compared to *frequent* stop-signals, but rather may reflect stimulus probability “oddball” effects. In the final phase of this thesis, an examination of response inhibition in impulsive populations revealed that non-clinical adults who showed high degrees of the impulsiveness personality trait did not suffer from an inhibitory deficit, but rather, were characterised by an over-active response process. In contrast, adults with Attention-deficit Hyperactivity Disorder, despite similar overt performance with non-clinical groups, showed a slower and under-active inhibition process that was compensated for through a reduction of response activation. These findings suggest that a deficiency in the stop-signal inhibition process is not associated with impulsive behaviours in general, but with a more clinical form of impulsivity. Together the findings from this thesis have presented an electrophysiological view of response inhibition in the stop-signal task that has: (a) furthered our understanding of the manifestation of inhibition in different inhibitory contexts and populations, (b) clarified the functional significance of the N2 and P3 components in the stop-signal task, and (c) provided an insight into the relationship between stop-signal inhibition and impulsivity.

## **Overview**

Inhibition of an ongoing response in the typical (simple) stop-signal task involves a simple response comprised of stop-signal detection and inhibitory activation (Logan, 1994). A review of the literature revealed few attempts to examine stop-signal inhibition relative to response inhibition in other tasks, or to examine the effect of complicating the stop-signal inhibitory response. One aim of this thesis was to examine the nature of response inhibition in different contexts. Specifically, simple inhibition in the stop-signal task was examined relative to: (a) the inhibition of a prepotent prepared (as opposed to ongoing) response as derived during cued go/nogo task (Study I, Chapter 4), and (b) the inhibition of an ongoing response in the selective stop-signal task, which includes an additional stimulus discrimination to determine whether or not inhibition is required (Study II, Chapter 5). Study I extended on previous research by providing a comparison of stop-signal and nogo inhibition with examination of the topographic distribution of both early/exogenous (N1 and P2) and later/endogenous (N2 and P3) ERP components in a 3 x 3 matrix, providing information about the distribution of activity across lateral and sagittal regions. Study II (Chapter 5) provided the first within-subject comparison of ERPs between simple and selective versions of the stop-signal task. It was determined from these findings that nogo and simple stop-signal inhibition manifested differentially in the ERPs, reflecting the activation of different underlying neural processes of inhibition, and that inhibitory processing was faster for the latter form of inhibition. The inclusion of a stimulus discrimination in the selective stop-signal response did not affect the latency of inhibitory processing components and the manner in which responses were stopped, relative to the simple stop-signal response.

Although the N2 and P3 components have been generally linked with response inhibition in the literature, their exact functional roles were unclear within the stop-signal task, particularly for the auditory-evoked N2, which was believed to reflect inhibition in the visual modality only. Therefore, another aim of this thesis was to elucidate the functional roles of the auditory-evoked N2 and P3 components in the stop-signal task. As the successful inhibition of fast responses was predicted to be associated with *greater* or *faster* inhibitory activation, Study III (Chapter 6) examined the response inhibition hypothesis for stop N2 and P3 through a comparison of fast and slow RT groups, while the response conflict hypothesis was examined by comparing stop N2 relative to the response-locked Ne. Finally, the role of error-related processes on failed stop trials was also examined. Therefore, Study III provided (a) the first ERP comparison of slow and fast RT groups in the stop-signal task, and (b) the first attempt to explicitly examine the response inhibition and conflict hypotheses for the stop N2 and P3. It was found that successful stop N2 and P3 were functionally distinct, whereby the former component was associated with greater control over responses in frontal regions, and the latter component associated with the site or manifestation of the urgent stop-signal inhibition process near or in the motor or premotor cortex. Furthermore, failed stop trials were found to reflect the aggregate of stop-signal and response-locked, error-related activity.

It is generally accepted in the stop-signal literature that varying stop-signal probability affects inhibitory difficulty and, thereby, the inhibition process (Logan, 1994; Logan, Cowan, & Davis, 1984; Ramautar, Kok, & Ridderinkhof, 2004). However, it was unclear whether modulations of ERP amplitudes for stop-signals presented on fewer trials, relative to more frequently presented stop-signals, reflected the variation in inhibitory activation (Ramautar et al., 2004), or was merely a product of the probability-related

oddball effect (see generally Duncan-Johnson & Donchin, 1977). Study IV (Chapter 6) addressed this issue by providing an examination of the effect of varying stop- and ignore-signal probability on ERP components. Findings showed probability effects of similar magnitude for stop- and ignore-signal trials, suggesting that modulations of ERP amplitudes did not solely reflect variations in inhibitory requirements, but rather, reflected oddball effects.

Deficient response inhibition has been intrinsically linked to impulsivity (Logan, Schachar, & Tannock, 1997; Schachar & Logan, 1990) and is believed to underlie impulsive behaviour in ADHD (e.g. Barkley, 1997). This thesis extended the response inhibition literature via (a) an ERP investigation of response inhibition in subjects who report extreme low and high degrees of the impulsiveness personality trait (Study V, Chapter 9), and (b) an ERP investigation of response inhibition in adults with ADHD in simple and selective versions of the stop-signal task, relative to low and high (non-clinical) impulsivity groups (Study VI, Chapter 10). These examinations provided an insight into the role of stop-signal inhibition in underlying impulsivity. These studies revealed that deficient stop-signal inhibition did not underlie all impulsive behaviours per se, but rather, was related to a more dysfunctional form of impulsivity, as found in ADHD.



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## **Abbreviations**

ACC	Anterior Cingulate Cortex
ADHD	Attention-deficit Hyperactivity Disorder
Ag/AgCl	Silver/Silver Chloride
ANOVA	Analysis of Variance
ASRS	ADHD Self-Report Scale for Adults
BIS	Barratt Impulsiveness Scale
CD	Conduct Disorder
CNS	Central Nervous System
CNV	Contingent Negative Variation
CPT	Continuous Performance Task
DA	Dopaminergic Activity
DF	Degrees of Freedom
DSM-IV	Diagnostic Statistical Manual of Mental Disorders, 4 <sup>th</sup> edition
DSM-IV-TR	Diagnostic Statistical Manual of Mental Disorders, 4 <sup>th</sup> edition-revised
EEG	Electroencephalogram
EMG	Electromyogram
EOG	Electrooculogram
ERN	Error-related Negativity (see also Ne)
ERP	Event-related Potential
fMRI	Functional Magnetic Resonance Imaging
FrSBe	Frontal Systems Behaviour Self-Rating Scale
FSRT	Failed Stop Reaction Time
GHQ-28	General Health Questionnaire-28
IFC	Inferior Frontal Cortex
IFG	Inferior Frontal Gyrus
IGRT	Ignore-signal Reaction Time
ISI	Inter-Stimulus-Interval
IVE	Impulsiveness/Venturesomeness/Empathy Scale
LPC	Late Positive Complex
LRP	Lateralised Readiness Potential
MANOVA	Multivariate Analysis of Variance
MAO	Monoamine-oxidase
MEG	Magnetoencephalography
MRT	Mean Reaction Time
MSW	Mean Slow Wave
NA	Noradrenergic Activity
Ne	Error-Negativity
Nd	Negative Difference
NSW	Negative Slow Wave
PCA	Principal Components Analysis
Pe	Error-Positivity
PFC	Prefrontal Cortex
PSW	Positive Slow Wave
PN	Processing Negativity
RP	Readiness Potential
RPM	Raven's Progressive Matrices Test
RT	Reaction Time
SD	Standard Deviation
Sn	Tin
SPAM	Significance Probability Albert Mapping
SSRT	Stop-signal Reaction Time
SMA	Supplementary Motor Area

WURS	Wender Utah Rating Scale
ZRFT	Z-score of Relative Finishing Time

# **1. Inhibition**

## **1.1 Chapter Aims**

The aims of this chapter are to: (a) provide a general introduction to the concept of inhibition, (b) describe the stop-signal task, (c) examine how the race model applies to the stop-signal task, (d) address the factors mediating stop-signal task performance, (e) summarise the stop-signal inhibition literature for young, non-clinical adults, and (f) compare the stop-signal task with another laboratory measure of inhibition, the go/nogo task.

## **1.2 General Introduction**

In a dynamic environment, it is essential that we are able to adjust our thoughts and behaviour in line with external cues, as well as our own internal directions. This involves an eloquent interaction of response *activation* and *inhibition* processes. Although there is a vast literature on the mechanisms involved in the preparation and execution of responses, whether they be of a motor or cognitive nature, research has only begun to examine the effect of inhibitory processes. Historically, the absence of overt movement was viewed merely as the consequence of a lack of motor action (Diamond, Balvin, & Diamond, 1963). However, at present, researchers understand the necessity to examine both action and inaction, and have moved towards conceptualising inaction as the effect of an active suppressive agent on motor activity, rather than a by-product of reduced motor activation (Diamond et al., 1963).

The English Oxford Dictionary (Oxford, 1933) defines inhibition as: “The action of preventing, hindering, or checking” (Definition 3, p. 295). Brunton (1883 as cited in Oxford, 1933) states:

By inhibition we mean the arrest of the functions of a structure or organ, by the action upon it of another, while its power to execute those functions is still retained, and can be manifested as soon as the restraining power is removed.

Clark (1996) defines inhibition broadly as “any mechanism that reduces or dampens neuronal, mental, or behavioural activity” (p. 128). As is obvious from these definitions, inhibitory control can occur at a number of levels of functioning, but in one form or another, they all involve suppression. A range of behaviours from diverse areas of neuroscience and psychology are subject to inhibitory processes (see Clark, 1996; Kok, 1999 for a review). For example, at the neuronal level, inhibitory effects have been observed in the selective inhibition of single-cells in the visual cortex to allow selective attention towards a target stimulus and the inhibition of distractors in the environment (Moran & Desimone, 1985). At the cognitive level, the activation of a previous task-set may “compete” with a new task-set, producing longer responses than would typically be found (Karayanidis, Coltheart, Michie, & Murphy, 2003). Finally, at the motor level, inhibition of a motor response is the most direct expression of inhibitory control because there is a clear definition of the changes that result from the inhibitory act (i.e. the inhibition of a motor response) (Logan, 1994). The defining element of these different mechanisms of inhibition is that they have the capacity to reduce activity.

The form of inhibition examined in this thesis is response (or behavioural) inhibition. Response inhibition is considered to reflect the action of a higher-order executive function enforcing control over the cognitive system by suppressing or

delaying an action (Barkley, 1997). Barkley (1997) distinguishes behavioural inhibition as reflecting three interconnected processes, including (a) the inhibition of an initial prepotent response to an event, (b) the inhibition of an ongoing response, which permits a delay in the decision to respond and (c) interference control, which protects the period of delay from competing responses and events. Although all three processes are important in defining inhibitory control, the inhibition of an ongoing motor response is the focus of this thesis due to its utility in elucidating individual differences in inhibitory control in normal behaviour and psychopathology (see Logan, 1994 for a review).

### **1.3 Executive Functions**

Executive functions are a set of higher-order processes that are predominantly private (cognitive) self-directed actions that maintain goal-directed behaviour (Barkley, 1997; Pennington, 1996). They include, but are not limited to, functions such as self-regulation, sequencing of behaviour, flexibility of thinking or responding, the use of self-directed speech, rules or plans, response inhibition, planning and organisation of behaviour, and goal-directed intentional actions (Tannock, 1998). In particular, executive functioning is required when effective new plans of action need to be formulated and appropriate sequences of responses need to be selected and scheduled (Robbins, 1998). These processes may be regarded as “top-down” effects, in contrast to “bottom-up” effects, which reflect basal, stimulus-driven processes.

Executive functions have consistently been linked with the frontal lobes, in particular, the prefrontal cortex (PFC) (Miller & Cohen, 2001; Pennington, 1996; Roberts & Pennington, 1996). Strong support for this association comes from patients with frontal lobe lesions who show deficiencies in categorisation and sorting (e.g. Stuss

et al., 2000), planning and problem solving (e.g. Shallice & Burgess, 1991), as well as, being easily distracted and unable to delay gratification (e.g. Dias, Robbins, & Roberts, 1997; Sonuga-Barke, Taylor, Sembi, & Smith, 1992). However, the PFC has extensive connections with a number of other cortical and subcortical structures, including the parietal cortex, basal ganglia, the limbic systems and thalamus (Kaufer & Lewis, 1999). Therefore, executive functions, including response inhibition, may involve a widespread neural network (see section 3.4.3 for further details).

## **1.4 Response Inhibition**

In real-life situations, response inhibition is a vital function that allows us to make fine motor adjustments such as typing on a keyboard, or gross inhibitory actions, such as stopping your foot from pressing the accelerator pedal in a car. The inhibition of an ongoing motor response is the first step towards a new course of action (Logan, 1994). Barkley (1997) suggests that response inhibition is central to the implementation of the other executive functions in that it provides the cognitive system with a necessary delay for them to occur. However, although inhibiting a response is an action unto itself, this action is unobservable. Behaviourally, researchers may only infer that the inhibitory response had been executed by the absence of a response, unlike the response process, which can be observed and measured directly. The type of inhibitory motor control this thesis is mostly concerned with is a phasic inhibitory response to an external event (Logan & Cowan, 1984; Logan, Cowan, & Davis, 1984), rather than tonic forms of inhibition such as reduced response readiness (van den Wildenberg, van Boxtel, & van der Molen, 2003; van den Wildenberg, van der Molen, & Logan, 2002).

Numerous behavioural tasks have been developed for the laboratory to measure response inhibition. Some examples of these include continuous performance tasks



(e.g. Tekok-Kilic, 2001), Stroop tasks (e.g. Bush et al., 1999), Eriksen flanker tasks (e.g. Iwaki, Miyatani, & Toshima, 2003), delay of gratification tasks (e.g. Douglas, 1983; Sonuga-Barke et al., 1992), and the Matching Familiar Figures Task (e.g. Weyandt & Willis, 1994). While many of these tasks purport to measure response inhibition, most actually measure a complex aggregate of cognitive processes and lack the specificity to distinguish between them (Tannock, 1998). The two most commonly used laboratory tasks for measuring response inhibition include the go/nogo (e.g. Falkenstein, Hoormann, & Hohnsbein, 1999; Falkenstein, Koshlykova, Hoormann, & Hohnsbein, 1995b) and stop-signal tasks (Logan, 1994).

### 1.5 The Stop-signal Task

The best measure, to-date, of the inhibition of an *ongoing* response is the stop-signal task (Oosterlaan, 1998; Pliszka, Liotti, & Woldorff, 2000; Quay, 1997). Several studies have demonstrated its reliability and validity as a measure of response inhibition (Kindlon, 1995; Tannock, Schachar, Carr, Chajczyk, & Logan, 1989). In a typical stop-signal task, the subject is required to perform a primary choice reaction time (RT) task, and on a portion of trials, a stop-signal instructs the inhibition of the go response (Logan et al., 1984). Typically, a visual primary task and auditory stop-signals have been used, although this is by no means the only available design. Subjects are instructed to respond accurately and quickly to the primary task, but to stop their response if a stop-signal occurs. This involves an absolute form of all-or-none inhibitory response (Logan, 1994).

The stop-signal task allows a clear definition of the conditions that trigger response activation (i.e. the go stimulus) and inhibition (i.e. the stop-signal), and the changes that result from the inhibitory act (i.e. the inhibition of response activation).

“Go-processes”<sup>1</sup> involved in the execution of a motor response (termed the go response) are triggered by the presentation of the primary task go stimulus and include: (a) stimulus identification and registration, (b) discrimination and translation of the stimulus as requiring either a left or right hand response, and (c) the preparation and execution of the appropriate response. “Inhibition” processes involved in the stopping of the go response are triggered by the presentation of the stop-signal and consist of: (a) stop-signal identification and registration, and (b) the activation of the inhibition process. However, these processes do not necessarily have to be completed in a serial manner, but rather, may occur in parallel (de Jong, 1992; Logan, 2002).

A performance measure of inhibition that is unique to the stop-signal task is the latency of the inhibitory response. Although the latency and variability of the go response can be observed directly, the internally-generated inhibitory response is unobservable. Known as Stop-signal Reaction Time (SSRT) (Logan & Cowan, 1984; Logan et al., 1984), this measure can be estimated using a mathematical model of inhibition known formally as the “Horse Race Model” (see sections 1.6 generally, and 1.6.1 specifically on how to estimate SSRT).

## **1.6 The Horse Race Model of Inhibition**

The advantage of the stop-signal task over other inhibition tasks is that the factors mediating performance are outlined by the well-established race model (Logan & Cowan, 1984; Logan et al., 1984). According to the model, the go processes comprising the go response and the inhibition processes comprising the stop-signal

---

<sup>1</sup> “Go-processes” refers to the individual components that comprise the “go response”, while the “go response” refers to the total response that is comprised of a number of processes. Similarly, “inhibition processes” refers to the individual components that comprise the total “inhibitory response”, and vice versa. Note, however, that singular reference to the “inhibition process” refers only to the process involved in the actual inhibitory action, and not to perceptual processes preceding this.

inhibitory response “race” independently against each other. Whether the go response is inhibited or not depends upon the relative finishing times of the two sets of processes. If the go response finishes the race before the inhibitory response, the go response is executed. If alternatively, the inhibitory response finishes the race before the go response, the go response is stopped. The finishing times of the go and inhibitory responses are assumed to be stochastically independent and random variables; therefore, the outcome of the race is a matter of probability (Logan, 1994).

### *1.6.1 Estimating Stop-signal Reaction Time (SSRT)*

SSRT was estimated in this thesis using what has come to be known as the “conventional method” (Logan, 1994), which assumes that SSRT is relatively constant (Logan, 1981). SSRT refers to the duration of the inhibitory response from the onset of the stop-signal to the point where the go process is stopped. Although the onset of the stop-signal is known because this is experimentally controlled, the point at which the go process is stopped must be estimated, because it cannot be observed directly. This is achieved by integrating the Go RT distribution until the area under the integral equals the probability of responding. This is illustrated in Figure 1.1 by moving the vertical line across the distribution until the left portion equals the probability of responding. The value of the RT at the vertical line is the estimated time that the go process was stopped, because RTs to the right of this line reflect those that were inhibited, while RTs to the left of this line reflect those that were executed (Logan, 1994). Once this point is estimated, the stop-signal delay can be subtracted to obtain the SSRT. Procedurally, this involves: (a) rank-ordering Go RTs from no-signal trials, (b) finding the  $n$ th Go RT, where  $n$  is the probability of responding at a particular delay multiplied by the number of Go RTs in the whole block, and (c) subtracting the stop-signal delay from the  $n$ th Go

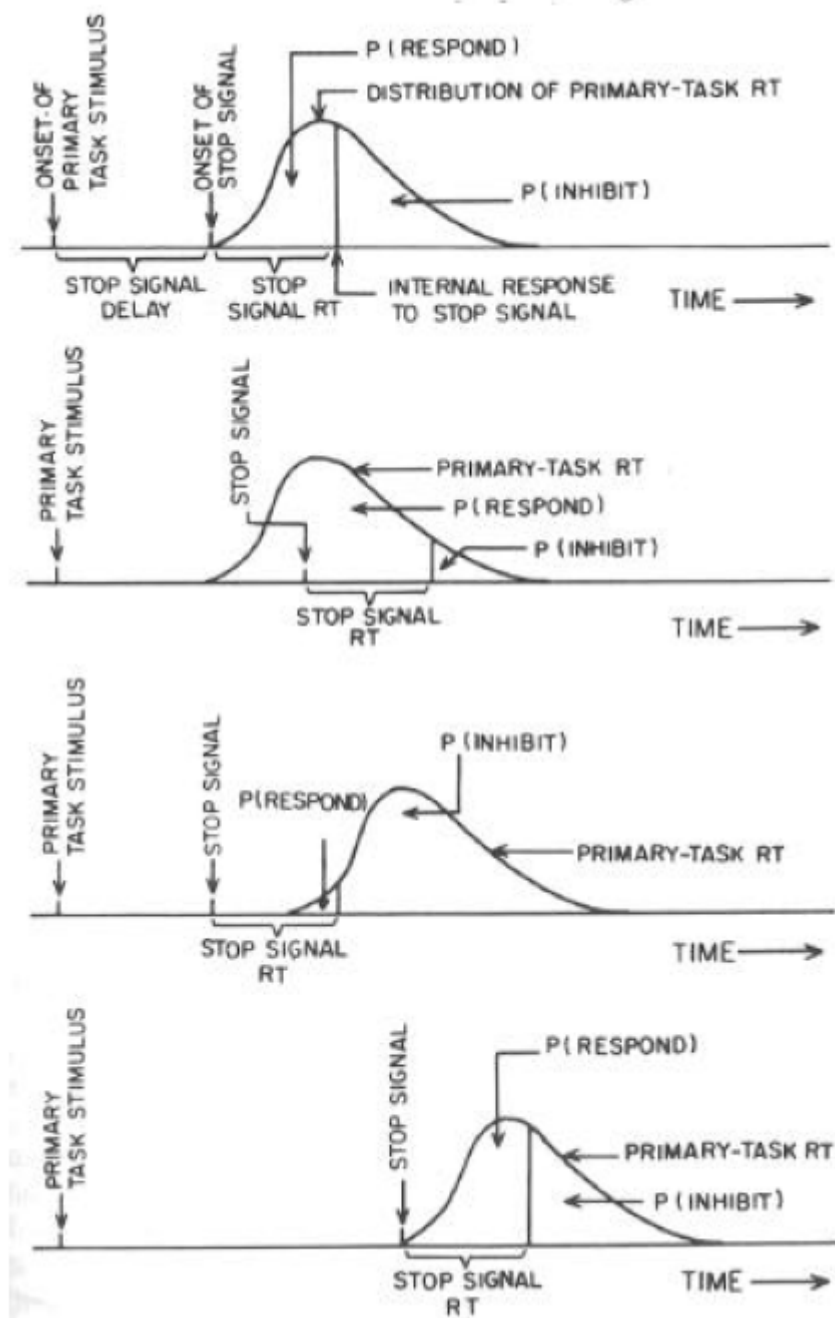
RT (Logan, 1994; Logan & Cowan, 1984). This is performed for each stop-signal delay, with the resultant SSRTs averaged together to give an estimate of average SSRT across stop-signal delays (termed SSRT<sub>av</sub>).

Using simulations of stop-signal task performance, SSRT<sub>av</sub> across the stop-signal delays has been shown to provide an accurate measure within 5 ms of the true SSRT and is robust against even large violations of the race model's assumptions of independent processes and a constant SSRT (see below)(Band et al., 2003b).

### *1.6.2 Inhibition Function*

An informative method of examining inhibitory performance is to plot an inhibition function, that is, the major dependent variable in the stop-signal task which reflects the probability of inhibiting the go response (i.e. a successful stop) at each stop-signal delay (Logan & Cowan, 1984; Logan et al., 1984). The main independent variable in the stop-signal task is the interval between the go stimulus and the stop-signal, known as the “stop-signal delay”. Figure 1.1 depicts the assumptions and predictions of the race model, illustrating how variations in stop-signal delay and the latency of the go response affect inhibition probability (taken from Logan & Cowan, 1984, p. 278). Inhibition probability has shown to be partially dependent upon the stop-signal delay across different effector systems (Lisberger, Fuchs, King, & Evinger, 1975) and tasks (Lappin & Ericksen, 1966). A stop-signal that is presented close to the onset of the go stimulus makes it easier to stop the go response, increasing the right portion of the RT distribution that reflects the probability of inhibition (see Figure 1.1, first panel).

In contrast, stop-signals that are presented closer to the expected point of response execution make it more difficult to stop the go response, due to the lack of time for the



**Figure 1.1** An illustration of the “Horse Race Model” taken from Logan and Cowan (1984, p. 278). In each panel, the curve reflects the distribution of primary task go RTs plotted as a function of time. The vertical line that cuts this distribution reflects the internal inhibitory response to the stop-signal. The portion of the distribution to the left of this line reflects the probability of responding given a particular stop-signal delay, while the portion to the right of the line reflects the probability of inhibition given a particular stop-signal delay. The first panel represents an example of “typical” stop-signal parameters and is used as reference for the other three panels. The figure illustrates the effect varying stop-signal delay and primary task RT on the probability of inhibition.

inhibition process to complete its race, increasing the left portion of the RT distribution that reflects the probability of responding (see Figure 1.1, second panel). As a result, successful stop trials will predominantly contain earlier stop-signal delays, while failed stop trials will consist of later stop-signal delays. Therefore, the stop-signal delay can bias the “race” in favour of one process over another (Logan et al., 1984).

Average inhibition probability is influenced by five factors: (1) the latency of the go process, (2) variability in the latency of the go process, (3) the latency of the inhibition process, (4) variability in the latency of the inhibition process, and (5) whether the inhibition process was triggered or not.<sup>2</sup> The interaction of these five factors can be observed in the distribution of the inhibition function. The latency of the go response is most often responsible for differences between groups and conditions in inhibition functions (Logan & Cowan, 1984). Holding all other factors constant, slower responses are easier to stop than faster responses due to the fact that the inhibition process has time to “catch-up” to the go process before it is executed (see Figure 1.1, third panel). However, delays in go RT can usually be compensated for if the stop-signal is delayed by a corresponding amount (see Figure 1.1, fourth panel and section 1.6.3). Similarly, all else being equal, a longer SSRT results in a greater proportion of failed stop trials, while a faster SSRT results in a greater proportion of successful stops.

Trial-to-trial variability in the latency of the go response affects the shape of the inhibition function. Large response variability leads to a flatter inhibition function, with similar inhibition probability across the delays, while less response variability leads to a steeper inhibition function where inhibition probability reduces significantly with an increase in stop-signal delay. If an inhibition function in one group or condition is

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<sup>2</sup> It should be noted that on a particular single stop-signal trial, inhibition probability is not influenced by variability of the response and inhibition processes because this measure refers to trial-to-trial differences.

flatter than another, even after accounting for the latency of the go process, a transformation can be applied to the data so that inhibition probability is plotted as a function of the relative finishing time of the go and inhibition processes in terms of standard deviation units. This transformation is known as ZRFT, that is, the relative finishing time represented as a *z*-score. Operationally, the mean (MRT) and standard deviation (SD) of go RT, as well as mean SSRT, are used to calculate ZRFT with the formulae:  $([MRT - \text{delay} - SSRT]/SD)$  (Logan & Cowan, 1984; Logan et al., 1984). This transformation accounts for the latency and variability of the go response, as well as, the latency of the inhibitory response (i.e. SSRT). If the inhibition functions are brought into alignment after this transformation, the difference in inhibition probability was due to one of the factors used to calculate ZRFT. If the functions are not brought into alignment, it can be concluded that poorer inhibition probability in a particular condition or group may be due either to greater within-subject variability in the latency of the inhibitory response or to the inhibition process not being triggered on every stop-signal trial (i.e. an under-active inhibition process) (Logan, 1994).

However, caution must be taken when the inhibition function is the only method of examining inhibitory performance. Recently, Band, van der Molen, and Logan (2003b) simulated performance in the stop-signal task and demonstrated that the ZRFT transformation did not completely remove differences in go process variability. The inhibition function was found to be affected by the variability and triggering rate of the inhibition process to a similar extent as go process variability, thereby, limiting the utility of the inhibition function in teasing apart these three factors. Furthermore, the inhibition function and its transformation appeared to be sensitive to violations of the independence assumption, resulting in a steeper slope. However, the advantages of plotting the inhibition function are that it provides valuable insight into overall

inhibitory performance across stop-signal delays (i.e. taking into account all five influencing factors) between conditions and groups, and allows, at least, the successful dissociation of the effect of the stop-signal delay and the latency of the go process on inhibition probability. It is suggested that an interpretation of the inhibition function would be aided by the examination of more direct measures of inhibition, such as electrophysiological responses.

### 1.6.3 *Stop-signal Delay*

The decision as to what method an experimenter should adopt to set stop-signal delay depends upon time restraints and precisely what the experimenter is interested in measuring (Logan, 1994). The simplest method for setting stop-signal delays is to present a number of fixed, arbitrary delays. For example, studies using this method typically set stop-signals at 0, 100, 200, 300 and 400 ms after the onset of the go stimulus. Delays are usually chosen with the intention of capturing the full range of inhibition probability (i.e. 10 to 90 %). Thus, it would be undesirable to have a stop-signal delay of 900 ms, for example, because most adults will have responded to the go stimulus by this time, resulting in a 0 % inhibition probability. Typically, stop-signal delays range from 0 to 500 ms, but this also depends upon the population being measured. Longer delays may be required when testing clinical populations due to slower response processing (Logan, 1994).

Using the *tracking method*, stop-signals are set to initially occur at a fixed interval, and then stop-signal delay is varied on-line to adjust for variability in inhibitory performance. If a subject inhibits the go response on a particular stop-signal trial, the stop-signal delay may be increased by 50 ms. Conversely, if a subject fails to inhibit the go response, the stop-signal delay is reduced by 50 ms. Although it has been



shown that this method provides the most accurate measure of SSRT (Band et al., 2003b), the inhibition function cannot be plotted because there are no set delays to act as a reference point between subjects. Furthermore, the tracking method does not allow the researcher to capture the inhibition of relatively equivalent stages of response processing between subjects (van der Schoot, Licht, Horsley, & Sergeant, 2002), which is an issue of primary importance in the examination of event-related potentials (ERPs). For example, some subjects may receive mostly short stop-signal delays, such that the inhibition process will act only on early preparational stages, while others may receive mostly long stop-signal delays with the inhibition process acting on later stages of processing (see section 2.6).

Thus, the present thesis used the method of presenting stop-signals at set intervals ( $x$ ) preceding each subject's expected point of response execution, estimated using mean go reaction time (MRT), which was updated after every block. Typically, the MRT from the first block is used to set delays in the second block, the MRT from the second block is used to set delays in the third block, and so on. For example, to set  $(MRT - x)$ , if one chooses  $x$  to equal 150 ms and the subject's MRT is 550 ms, this means that the stop-signal delay is  $(MRT-150)$  ms, which equates to 400 ms. This adjustment accounts for differences in MRT between different subjects, such that faster responders receive shorter delays and slower responders receive longer delays (see Figure 1.1, fourth panel).<sup>3</sup> Unlike the tracking method, due to the fact that stop-signals are presented relative to each subject's MRT, stop-signals will capture relatively equivalent stages of response processing between subjects.<sup>4</sup>

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<sup>3</sup> Although this method accounts for go process variability *between* blocks, which may result from practice effects or prolonging responses, it cannot account for go process variability *within* a block.

<sup>4</sup> Note that "exactly" equivalent stages of response processing can never be examined due to the fact that responding varies on a trial-by-trial basis (R. Oades, personal communication, 25 November, 2004).

Logan et al. (1984) tested the above three methods for setting stop-signal delay and showed that the different methods did not differentially affect performance on the primary task or the way in which the stop-signal was processed.

#### *1.6.4 Assumptions of the Race Model*

In order to estimate SSRT accurately, the race model states that two assumptions must be met. The first is that SSRT is a constant measure and the second is that the response and inhibition processes are independent. With respect to a constant SSRT, although it has been empirically shown that SSRT does vary, this has minor or negligible effects on estimating  $SSRT_{av}$  (Band et al., 2003b; de Jong, Coles, Logan, & Gratton, 1990).

Independence comes in two forms: contextual independence means that the duration of the go process is unaffected by the presence of the stop-signal, and that the duration of the inhibition process is unaffected by the presence of the go stimulus, while stochastic independence means that the durations of the go and inhibition processes are not correlated. With respect to contextual independence, Logan et al. (1984) found that SSRT in a choice-RT task was longer than that found in a simple-RT task. As the response to the stop-signal required the same simple-RT response between the two tasks, this evidence suggested a refractory effect on the inhibitory response due to the preceding go process. Thus, a violation of contextual independence appears to be an inherent characteristic of the stop-signal task when using a primary choice-RT task. The question is whether this violation is a serious one. Logan et al. (1984) noted that while SSRT was longer in the primary choice task, it was still significantly shorter than simple-RTs in a dual-task, suggesting that the refractory effect is relatively weak.

Conversely, studies have shown that the stop-signal affects the duration of the go process when you compare RTs in a typical choice-RT task with the RTs in the primary choice-RT component of the stop-signal task (e.g. Rieger, 2000, 1999; van den Wildenberg et al., 2003).

A violation of stochastic independence has been shown to affect some measures of SSRT (not including  $SSRT_{av}$ ) and the inhibition function (see Band et al., 2003b for a review). The independence assumption is typically tested using MRT to go stimuli on failed stop trials (i.e. Failed Stop Reaction Time; FSRT) (Logan & Cowan, 1984; Logan et al., 1984). The model predicts that FSRT should be faster than MRT on no-signal trials due to the fact that the RTs to the left of the vertical line in the RT distribution reflect fast RTs that escaped inhibition (see Figure 1.1). Furthermore, if the go and inhibition processes are independent, the mean of the observed FSRTs can be predicted on the basis of the mean of the distribution of RTs on no-signal trials corresponding to the failed stop portion (i.e. the probability of responding). However Band et al. (2003b) found that the observed RT minus predicted RT difference was not a valid test as it was affected by go process and SSRT variability.

#### *1.6.5 Summary*

The stop-signal task has a number of advantages over other inhibition tasks including, (a) being based on the race model of inhibition, (b) providing a clear definition of the conditions mediating inhibitory performance, and (c) providing a method of estimating SSRT. Inhibitory performance appears to be mediated by the stop-signal delay, the speed and variability of the primary go process, the speed and variability of the inhibition process, and the probability that the inhibition process will be triggered. Performance can be visually inspected by plotting inhibition probability as

a function of stop-signal delay or a transformation of delay. Although the inhibition function comes with some caveats, it can be examined in conjunction with more direct measures of inhibition (i.e. ERPs). Furthermore, stop-signal delay can be set relative to each subject's MRT to provide a measure of inhibition at relatively equivalent stages of response processing between subjects. Finally, although the race model makes assumptions about the independence of the go and inhibition processes and a constant SSRT, studies have shown that violations of these assumptions have minor effects on the estimation of  $SSRT_{av}$ .

## **1.7 Individual Differences in Stopping: A Selective Review**

The stop-signal task has been used in a vast number of studies to examine individual differences in response inhibition across a number of population groups and under various within-subject manipulations on inhibition. Although the stop-signal task has shown a particular utility in examining inhibitory deficits in child psychopathologies, the focus of this thesis is on response inhibition in the adult population, and therefore, the focus of the following literature review was on this population group. Furthermore, the review has been restricted to areas within the stop-signal literature which are relevant to the progression of research in this thesis.

### *1.7.1 SSRT in Young, Non-clinical Adults*

Young, non-clinical adults show a relatively stable latency of the inhibitory response, which has been estimated to be between 200 and 250 ms (Logan, 1994) across the inhibition of various types of discrete responses including key presses, hand movements and squeezes (for a review see Logan & Cowan, 1984), eye movements

(Lisberger et al., 1975; Logan & Irwin, 2000), as well as continuous movements such as speaking (Ladefoged, Silverstein, & Papcun, 1973), typing (Logan, 1982), arm movements (Logan, 1994), or thought (Logan, 1983) and arithmetic (Logan & Barber, 1985). These findings suggest that a single, global inhibition process may be utilised for the inhibition of an ongoing response in a variety of tasks, and furthermore, that response inhibition is a relatively simple task for young adults when required in an all-or-none manner (Logan & Cowan, 1984).

### 1.7.2 *The Selective (Stop/No-stop) Inhibitory Response*

Researchers using the stop-signal task to examine inhibition have primarily focussed on evoking a simple inhibitory response via a single stop-signal, which is analogous to a simple-RT task (Logan, 1994). There is only one signal that evokes one possible response. However, more complicated versions of the stop-signal task have been designed to examine the effect of increasing inhibitory difficulty on the inhibition process. A modified version of the stop-signal task involves presenting one of two possible tones, with subjects asked to inhibit responses upon the presentation of one tone (i.e. the stop-signal), but not the other (termed the ignore-signal in this thesis) (Bedard et al., 2002; Bedard et al., 2003; Riegler, 1986 as cited in Logan, 1994). This effectively converts the stopping part of the stop-signal task into a type of go/nogo task, where a discrimination is required to determine whether the tone is the stop-signal instructing response inhibition, or alternatively, the ignore-signal which carries no instruction (Logan, 1994). Previously, this form of inhibition has been termed *selective inhibition* (Bedard et al., 2002),<sup>5</sup> due to the selective nature of evoking the inhibitory

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<sup>5</sup>“Selective inhibition” has also been used in reference to inhibition in the stop-change task, whereby a single stop-signal indicates that one response should be replaced by a different response. In this case,

response, or *stop/no-stop* inhibition (Logan, 1994). Selective inhibition differs from simple inhibition in a number of respects. In the simple stop-signal task, subjects need only to detect the occurrence of an auditory stimulus to know that inhibition is required on a particular trial. In contrast, in the selective stop-signal task, subjects need to identify the auditory stimulus and *discriminate* it as either a stop- or ignore-signal, as well as, match the correct stop/no-stop response to the stimulus and maintain the stimulus-response rule in working memory. Thus, selective inhibition involves additional stages of processing and a greater load on working memory than simple inhibition (Bedard et al., 2003).

There are two published studies that have examined selective inhibition through discrimination between auditory stop-signals. Bedard et al. (2002) examined the development of selective inhibition across the life-span by instructing subjects to inhibit responses for a valid stop-signal and continue responding for an invalid tone. When results were compared to a similarly-designed study investigating simple inhibition, they found that SSRT in their selective stop-signal task was generally longer and developed at a different rate, while inhibition probability was reduced (Bedard et al., 2002; Williams, Ponsse, Schachar, Logan, & Tannock, 1999). However, this comparison was between studies, rather than within-subjects. Riegler (1986 as cited in Logan, 1994) employed a within-subjects design to compare the stopping of responses for all auditory stimuli (simple inhibition) with the stopping of responses for one but not the other stimulus (selective inhibition). They found a longer SSRT and reduced inhibition probability in the selective condition.

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there is selective inhibition in the *type* of motor output that is stopped. Stop-change inhibition has been shown to activate a functionally distinct inhibitory response to the selective inhibition examined in the present thesis, in which *all* motor output is stopped (de Jong, Coles, & Logan, 1995). It should be noted that throughout this thesis, the term selective inhibition will be used to refer to the inhibition of the go response to one stimulus (i.e. the stop-signal) but not another (i.e. ignore-signal).

A slower and different developmental trend for SSRT in selective compared to simple conditions has led to the notion of functionally-distinct inhibitory responses: a fast “global” mode that stops all responses in a non-selective manner versus a slow “local” mode used to selectively stop a response (Logan, 1994; van den Wildenberg & van der Molen, 2004b). However, the notion of two inhibitory modes does not imply separate inhibition processes (Band & van Boxtel, 1999). De Jong, Coles, and Logan (1995) suggested that the same mechanism was used in simple and selective inhibition conditions, with inhibition in the latter condition merely being activated later, once evaluation of go stimuli was complete. This suggests that the same inhibition process was engaged differentially between simple and selective conditions.

However, de Jong et al. (1995) used a different variant of the selective inhibition design where subjects were asked to inhibit one type of response but not another (e.g. inhibit right hand but not left hand responses) upon the presentation of stop-signals. Thus, stimulus discrimination was not directly reflected in the processing of the stop-signal but was dependent upon the completion of particular stages of go response processing. Studies employing this design have also found SSRT to be longer in selective than simple conditions (de Jong et al., 1995; Logan, Kantowiatz, & Riegler, 1986; van den Wildenberg & van der Molen, 2004b). While both methods outlined for examining selective inhibition create an inhibitory situation requiring a decision about whether or not to inhibit, they may evoke different inhibitory strategies and result in quite different inhibitory performance. The two methods, therefore, should be distinguished in research.<sup>6</sup>

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<sup>6</sup> The author thanks the anonymous reviewers from Psychophysiology for this suggestion in response to the review of “The effect of stimulus discrimination in the response to stop-signals: Simple versus selective inhibition” (Chapter 5).

Although researchers have exhausted examinations into the effect of a stimulus discrimination on the motor response in choice-RT tasks (e.g. Miller & Low, 2001; Smid, Fiedler, & Heinze, 2000), corresponding examinations into the effect of stimulus discrimination on the inhibitory response in the stop-signal task are sparse. The increase in RT for choice compared to simple-RT tasks is generally assumed to be due to the addition of response selection and preparation processes (Hackley & Valle-Inclan, 1999; Smid et al., 2000). Therefore, two important questions surround the issue of simple versus selective inhibition: (1) does the additional discrimination in the selective stop-signal task produce an additive effect on the latency of the inhibitory response, and (2) does selective inhibition activate a different type of inhibitory response, with independent neural generators, to simple inhibition? A within-subject comparison of simple and selective inhibition would provide greater insight into the effect of stimulus discrimination on inhibition processes and strategies (see Chapter 5).

### *1.7.3 Varying Stop-signal Probability*

In addition to complicating the inhibitory response, inhibition difficulty may be manipulated by varying the probability of the stop-signal. Typically, the stop-signal occurs on 25 to 30 % of primary task trials, which is an arbitrary value set to bias subjects towards responding to the go stimulus. Increasing the number of stop-signal trials has consistently been associated with an increase in Go RT and a decrease in the number of failed stop trials (Lappin & Ericksen, 1966; Logan & Burkell, 1986; Logan et al., 1984; Ollman, 1973; Ramautar, Kok, & Ridderinkhof, 2004). These findings suggest that increasing stop-signal probability encourages subjects to adopt a deliberate strategy of delaying and omitting responses in order to increase the likelihood of a successful stop. This strategy has been reported in a number of previous stop-signal



studies with subjects tending to wait longer the greater the frequency of the stop-signal (Lappin & Ericksen, 1966; Logan, 1981; Ollman, 1973). Nevertheless, the effects of varying stop-signal probability on inhibition processes can still be examined effectively by restricting this variability within a reasonable proportion of trials. It has been suggested that there is bias towards responding even when go and stop trials are equiprobable (Nieuwenhuis et al., 2003), therefore, varying the probability of the stop-signal within 0 – 50 % of trials maintains the bias towards responding (see Chapter 7).

Although varying stop-signal probability appears to affect the go process, it is unclear whether there is any concurrent effect on the inhibition process. Decreasing stop-signal probability encourages a bias towards activation and may be associated with impulsive behaviour such as fast and less accurate responding, as well as a poorer ability to inhibit inappropriate responses. Conversely, increasing stop-signal frequency may promote a slower and more cautious response style, accompanied by a greater control over response tendencies (Band, Ridderinkhof, & van der Molen, 2003a). As a consequence, it may be supposed that inhibition is more difficult when stop-signals are presented less frequently.

Most studies have found that although inhibition probability is affected by stop-signal probability, SSRT remains unaffected (Logan & Burkell, 1986; Logan et al., 1984; Ramautar et al., 2004). In contrast, van den Wildenberg et al. (2002) used a combination go/nogo and stop-signal task to examine the effect of varying the frequency of go trials. They found longer SSRT and Go RT in a condition with a 50 % go probability compared to an 80 % go probability (i.e. stop-signals were presented *less* frequently in the latter condition). They claimed that longer Go RT for less frequent go trials reflected a “reduced” readiness to respond and that, in line with Mattes and Ulrich (1997), a larger increment in response activation was needed to exceed the action

threshold, resulting in more forceful responses. Accordingly, this resulted in slower responses and slower stopping because forceful responses were more difficult to inhibit (van den Wildenberg et al., 2002).

These results were supported in a later study by the same researchers, where they reported longer SSRT for more forceful responses with a decrease in go probability (van den Wildenberg et al., 2003). However, these findings depart from the race model's independent processes assumption and Logan's executive-control theory (see section 1.8) that the lower subsidiary response process should have no effect on the high-order inhibition process (Band & van Boxtel, 1999; Logan & Cowan, 1984). Furthermore, the interpretation is counterintuitive to the generally accepted notions that slower responses are easier to inhibit (Logan, 1994) and that a reduced readiness to respond should aid, rather than impede, response inhibition (de Jong et al., 1995). Therefore, these findings are taken with caution. Chapter 7 examined the effect of varying stop-signal probability, and thereby inducing a cautious or impulsive response style, on inhibition processes and strategies.

#### *1.7.4 The Role of Subject Strategies*

An important but often forgotten factor within stop-signal task performance is the role of naturally occurring individual differences in response styles. Although all subjects receive the same instruction to respond quickly and accurately to the primary task, some subjects, nonetheless, continue to display a slower response style than typically found in simple and choice-RT tasks. In some cases, this may be due to naturally-occurring individual differences in response style (e.g. Lisberger et al., 1975), while in other cases, slower responses may reflect a deliberate strategy of prolonging responses in order to increase the likelihood of a successful stop (e.g. Lappin &

Ericksen, 1966). Delaying responses in this manner may violate the independent processes assumption, however, this circumstance appears to be a common problem in the stop-signal task (Lappin & Ericksen, 1966; Logan, 1981; Logan et al., 1984; Ollman, 1973). Although individual differences in response styles and strategies may seem like a nuisance factor in stop-signal task performance, they are, nonetheless, an interesting, naturally-occurring phenomenon that may provide insight into the use of different cognitive processes. The race model states that, holding all other factors constant, faster responses are more difficult to inhibit (Logan, 1994). As there were differences observed in response style between subjects in Study II (Chapter 5), this issue was further explored in Chapter 6 with an ERP comparison of fast and slow RT groups.

#### *1.7.5 Deficient Response Inhibition*

Although stopping appears to be a quick and relatively simple task for young, non-clinical adults, SSRT is somewhat prolonged for children (Ridderinkhof, Band, & Logan, 1999) and older adults (Kramer, 1994). Inhibition in the developmental literature has been linked with maturation of the frontal lobes (Kramer, 1994; van der Molen, 2000) and appears to follow a different developmental trajectory to the response process (Band, van der Molen, Overtom, & Verbaten, 2000). However, the domain in which deficient inhibition is most relevant for this thesis is its role in underlying impulsive response styles in healthy, non-clinical adults (Logan, Schachar, & Tannock, 1997) and adults with Attention-deficit/Hyperactivity Disorder (ADHD) (Aron, Dowson, Sahakian, & Robbins, 2003a; Schachar & Logan, 1990b), who have consistently shown problems in inhibitory motor control. Chapter 9 contains a detailed

review of the role of inhibition in the impulsiveness personality trait and in ADHD deficits.

#### *1.7.6 Summary*

In sum, SSRT appears to be a relatively fast and stable measure across a number of effector groups and tasks in young, non-clinical adults when the inhibitory response is a simple one. Longer SSRTs have been found in a selective inhibition variant of the stop-signal task that requires discrimination between a stop- and ignore-signal to decide whether inhibition is required on a particular signal trial. This increase in stopping latency has been interpreted as reflecting a slow “local” inhibitory mode, however, there is only one study that has employed a within-subject comparison of simple and selective inhibition, as measured through stop-signal discrimination. In contrast, increasing stop-signal probability appears to have no effect on SSRT but results in an increase in Go RT and inhibition probability. Finally, the race model states that slower responses are easier to stop than faster responses within subjects; however, the effect adopting a particular response style on inhibition processes has not been examined between subjects.

### **1.8 Logan’s Executive-Control Theory**

The consistent finding of a SSRT between 200 and 250 ms for young, non-clinical adults across the inhibition of various responses led Logan and Cowan (1984) to propose a single, “global” process for the inhibition of different responses. Although they did not suggest any candidate brain correlates of this process, the theory describes response inhibition as belonging to a hierarchical system, where an executive centre

enforces and evaluates control over lower-level subsidiary processes (Band & van Boxtel, 1999; Logan & Cowan, 1984). The subsidiary processes interpret and carry out orders until they are counteracted by the executive centre. Therefore, when the executive centre exerts an inhibitory effect onto responses by cancelling the support for subsidiary processes, response processes “grind to a halt” (Logan & Cowan, 1984, p. 322).

Logan and Cowan (1984) suggested that stop-signals and signals to modify the parameters of a response have “privileged” access to the executive centre, such that changes in top-down support are applied at higher levels than the subsidiary processes. Therefore, the latency of the inhibition process is unaffected by the characteristics of the go process (Band & van Boxtel, 1999). In contrast, signals that require an overt response which is different from the first response, such as in the stop-change task, are associated with a need to restructure response processes in line with the new intended output (Logan & Cowan, 1984). This results in a slower inhibitory response, which has been described as a slower “local” mode of inhibition (Logan & Burkell, 1986).

## 1.9 The Go/Nogo Task

The stop-signal task has been associated with the go/nogo task because they both require the execution of a response on a greater proportion of trials, and the inhibition of that response on a fewer proportion of trials. In the go/nogo task, subjects perform a choice-RT task where they respond to the *go stimulus* and withhold that response to the *nogo stimulus*. Typically, nogo trials are less frequent than go trials, which encourages a bias towards responding, with subjects more likely to prepare a response at the beginning of a trial. Researchers have suggested that there may even be a bias towards to the go response when go and nogo trials are equiprobable (Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003). As there is a

tendency towards responding in the go/nogo task, rather than not responding, it is believed that nogo trials are associated with the activation of inhibitory processes (Kok, 1986) to stop the *prepared*, prepotent go response (Barkley, 1997). A variant of this task is the cued go/nogo task whereby a cue appears at the beginning of a trial and warns the subject to prepare a response for an imminent stimulus. The cue acts to increase the level of response preparation and, therefore, the level of inhibitory activation required to stop the response. The major dependent variable in the go/nogo task is the probability of failed stops (or false alarms). The probability of failed stops may vary with the frequency of go stimuli (Pfefferbaum & Ford, 1988) and the difficulty of discrimination between go and nogo stimuli (Pfefferbaum, Ford, Weller, & Kopell, 1985), as well as whether subjects adopt a fast or slow response style (Falkenstein et al., 1999).

The go/nogo and stop-signal tasks may be considered to be similar when the stop-signal occurs at the same time as the go stimulus (i.e. stop-signal delay is zero) (Band & van Boxtel, 1999). However, despite similarities between the go/nogo and stop-signal tasks, they differ in a number of respects. In the go/nogo task, go and nogo stimuli occur on individual trials, while in the stop-signal task, stop-signals are presented either at or after the onset of the go stimulus on the same trial. Therefore, inhibition in the go/nogo task may be evoked relatively early, during response preparation, while inhibition in the stop-signal task may be evoked at variable stages of response processing, from preparation to the point of actual execution (see de Jong et al., 1990 for an investigation into the negligible effect of ballistic processes; Osman, 1986). Furthermore, as the response is ongoing in the stop-signal task, inhibition should be more difficult relative to the go/nogo task (Rubia et al., 2001).

Another important difference is that the stop-signal is the only auditory stimulus in the typical stop-signal task, therefore, subjects may merely need to detect the occurrence of an auditory stimulus before evoking inhibitory processes. In contrast, in the go/nogo task, subjects are required to perform a categorical stimulus discrimination to determine whether the auditory stimulus requires a go or nogo response (Rubia et al., 2001; van Boxtel, van der Molen, Jennings, & Brunia, 2001). Therefore, although there may be a greater load on inhibition processes in the stop-signal task, there may be a greater load on discrimination and response selection processes in the go/nogo task.

As in the comparison of simple and selective inhibition, there is debate about whether the inhibition of a prepared response and the inhibition of an ongoing response may involve different cognitive processes (Mehta, 2002; Rubia et al., 2001), or whether the same process may merely proceed in a different manner (van Boxtel et al., 2001). However, few studies have directly compared the stopping of a prepared response with that of an ongoing response. Chapter 4 provided a comparative examination of the performance in the typical stop-signal task relative to the go/nogo task.<sup>7</sup>

### **1.10 The Horse Race Model: Not a “Process” Model of Inhibition**

The success of the race model lies in its predictive utility and its generality. It provides an insight into the relationship between the go and inhibition processes in terms of RTs, but fails to consider the nature of these processes and how they actually succeed in interrupting responding. Although the race model has been shown to account for data very well in simulation studies (Band et al., 2003b; de Jong et al.,

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<sup>7</sup> Nevertheless, the stop-signal task is the main task used throughout this thesis as it has a number of advantages over other inhibition tasks, making it more suitable for investigations of response inhibition (see section 1.6).

1995), the weakness of the model is that it does not consider the distinct stages that that comprise the go and inhibitory responses. The model, however, can be used to test hypotheses about the nature of the underlying processes, such as whether the inhibition process was “under-active” in a particular condition or group relative to another. Logan (1994) states that the race model is not the final answer to questions about response inhibition, and that a complete picture can only be attained by considering the “details of the processes that the race model treats abstractly” (p. 209).

A number of methods are available for investigating the nature of stop-signal inhibition including an examination of: (1) stop-signal inhibition with other forms of inhibition,<sup>8</sup> (2) within-subject factors that affect inhibition, (3) underlying neural processes of inhibition in the stop-signal task, and (4) deficiencies in inhibitory processing (Logan, 1994; Van den Wildenberg, 2003). These four methods were used as the basis for the studies in this thesis. The first method was adopted in the first two studies where inhibition in the simple stop-signal task was compared to inhibition from a cued go/nogo task (Chapter 4) and then to a more complicated, selective stop-signal task (Chapter 5). As a result of finding large variability in responding between subjects in Study II (Chapter 5), Study III (Chapter 6) explored the effect of adopting a fast or slow response style on inhibition processes and strategies. The second method of investigating the nature of inhibition spurred Study IV (Chapter 7) where stop-signal probability was varied within-subjects to examine the effect of inducing a cautious or impulsive response style on inhibition processes. The final two studies incorporated the fourth method, with an examination of inhibition in non-clinical individuals displaying

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<sup>8</sup> Although Logan (1994) was referring to the interaction of stop-signal inhibition with another form of inhibition *within-tasks*. The authors believe that a comparison of stop-signal inhibition with different variants of response inhibition *between-tasks* is also an interesting comparison that provides insight into the nature of stop-signal inhibition.



extreme levels of impulsivity (Chapter 8) and in adults with ADHD (Chapter 9). To examine the underlying neural processes of inhibition in the stop-signal task (third method) ERPs were measured in each of the studies, providing an insight into the temporal and spatial properties of the inhibition processes. In the following chapter, we consider the measurement of ERPs in the stop-signal task.

## **2. Event-related Potentials in the Stop-signal Task**

### **2.1 Chapter Aims**

The aim of this chapter is to provide an examination of ERP components reported in previous stop-signal studies. Specifically, this chapter: (a) provides a general introduction into ERPs, (b) outlines issues related to the identification of ERP components, (c) addresses some conceptual issues related to ERPs in the stop-signal task, (d) reviews literature on stimulus- and response-locked ERPs in the stop-signal task, and (e) examines the lateralised readiness potential (LRP).

### **2.2 General Introduction**

ERPs are small, phasic, voltage fluctuations in response to a sensory, cognitive or motor event (Coles & Rugg, 1995). In contrast to performance measures, ERPs provide insight into the temporal and spatial properties of the neural processes underlying a particular response, whether it be overt or covert. ERPs recorded at the scalp represent the net electrical fields associated with the synchronous activity of large neuronal populations that are geometrically oriented to produce fields measured at the scalp (Allison, Wood, & McCarthy, 1986). It is believed that this activity is chiefly due to the summation of excitatory and inhibitory post-synaptic (dendritic) potentials, rather than axonal action potentials (Coles & Rugg, 1995).

The average ERP is derived from the electroencephalogram (EEG) by averaging a number of time segments of the EEG (termed epochs), time-locked around the event of interest. Averaging a number of epochs is a signal extraction technique that is based on the assumptions that: (a) the ERP is a consistent response and temporally related to

the event of interest, (b) activity not time-locked to the event of interest is considered random “noise” which can be attenuated with averaging, and (c) the degree to which random activity is attenuated is proportional to the square root of the number of epochs in the average (i.e. signal/noise ratio is improved by increasing the number of epochs in the average). Therefore, averaging a number of epochs acts much like a low-pass filter, attenuating activity unrelated to the target event (Coles & Rugg, 1995).

### **2.3 The Electroencephalogram (EEG)**

The EEG shows the fluctuation of electrical brain activity over time and is comprised of spontaneous electrical brain activity (termed noise) and the brain’s responses to either external or internal events. A common practice is to record EEG from the scalp in a non-invasive manner using silver/silver chloride (Ag/AgCl), or tin (Sn) electrodes. The location of electrode sites typically follows the international 10-20 system, which positions electrodes either 10 or 20 % of the distance from the nasion or inion (Jasper, 1958). In this system, electrodes are specified in terms of their locations along the sagittal (frontal, central, parietal, occipital) and lateral (left, midline, right) planes. Amplitude at each electrode site is measured in relation to a “reference”, which may consist of a single or pair of linked electrodes. The reference chosen must be a site that is relatively unaffected by electrical activity.

The EEG signal reflects the summation of multiple waves differing in frequency (measured as cycles/second, in Hertz; Hz), with amplitude varying between –100 and +100 microvolts ( $\mu$ V) (Coles & Rugg, 1995). Analysis of the EEG in the frequency domain consists of dividing the signal into frequency bands. Standard frequency bands include: Delta (0.5 – 3.5 Hz), Theta (3.5 – 7.5 Hz), Alpha (7.5 – 12.5 Hz) and Beta (12.5 – 22.5 Hz) (Gasser, Verleger, Bacher, & Sroka, 1988). As the EEG signal

includes frequencies that may not be of interest to the researcher, filters can be used to attenuate activity above and below a specified range. Typically, cognitive processes that are of interest to the researcher have a frequency of less than 30 Hz (Coles & Rugg, 1995). However, higher frequencies may be filtered out when researchers are interested in isolating slow-wave potentials, such as the readiness potential (i.e. a slow-wave negative potential generated in the motor cortices by response-related activity).

## 2.4 Event-related Potentials (ERPs)

### 2.4.1 General

The ERP waveform consists of a number of positive- and negative-going peaks varying in magnitude (i.e. amplitude), which are typically described by their: (a) polarity, (b) peak latency, (c) topographic distribution, and sometimes, (d) by their response to experimental manipulation. For example, a negative peak occurring approximately 100 ms after stimulus onset may be called the *N1* (or *N100*) component.<sup>9</sup> Furthermore, if the *N1* shows maximal amplitude in the central region, the component may be described as the *central N1*. Variations in the amplitude, latency and topographic distribution of ERP components with experimental manipulation allow inferences to be made about the nature of cognitive functions that these components reflect, and their temporal sequencing. Generally, peak latency provides an indication of the timing of the process reflected by the component, while amplitude reflects the degree of engagement by that process (Coles & Rugg, 1995). Differences in the scalp distribution of a component are interpreted to reflect differences in the generators of

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<sup>9</sup> In line with Coles and Rugg (1995), the term *component* is used to refer to a deflection in the waveform that is associated with a particular cognitive process. However, the terms *peak* or *potential* are used as a theoretically-neutral terms when referring to this characteristic of the ERP waveform.

underlying sources, and are indicative of different cognitive processes (Donchin, Ritter, & McCallum, 1978; Picton et al., 2000; Spencer, Dien, & Donchin, 2001).

The presentation of stimuli in any modality elicits a series of potentials in the ERP waveform that may be dissociated into early *exogenous* components, reflecting the activity of the sensory pathways, and later *endogenous* components, which represent information processing that may or may not be elicited by the stimulus event (Picton et al., 2000). Exogenous components are invariably elicited if the sensory system is undamaged, and are influenced by the physical parameters of the stimulus, but are insensitive to information processing demands (Fabiani, Gratton, & Coles, 2000). In contrast, endogenous components vary with information processing demands and can be either evoked to a stimulus or emitted when a cognitive process occurs independently of any stimulus. However, the exogenous-endogenous dichotomy is an oversimplification, as even early sensory components appear to be modulated by cognitive manipulations (Coles & Rugg, 1995). Generally, components evoked within 100 ms of the stimulus tend to be more exogenous, while those occurring later show endogenous characteristics.<sup>10</sup>

It should be noted that ERPs may be elicited by stimuli presented in auditory, visual or somatosensory modalities. While purely endogenous components are typically invariable across modality, components displaying exogenous characteristics vary in scalp distribution between modalities. Therefore, components observed in different modalities that have the same polarity and latency, but different scalp distribution, may be representative of different processes. The primary focus of this thesis was on ERPs elicited to stimuli in the auditory modality.

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<sup>10</sup> The term “mesogenous” has been used to describe components, typically in the 100 to 300 ms latency range, which display both exogenous and endogenous characteristics.

### 2.4.2 *Topographic Distribution*

Simultaneous recordings from multiple electrode locations are required to disentangle overlapping ERP components on the basis of their topographies and to measure different ERP components that may be optimally recorded at different scalp sites (Picton et al., 2000). While topographic analyses provide a description of the relative distribution of activation across the scalp, they may provide limited insight into the generators of scalp-recorded peaks. Because the brain acts as a volume conductor, activity from one region may propagate to another region (Coles & Rugg, 1995).

Under the assumption that a component is defined by its scalp distribution (see section 2.4.1), among other characteristics, different scalp distributions indicate a different component (Donchin et al., 1978; Picton et al., 2000; Spencer et al., 2001). In the analysis of the scalp distribution of a component, Picton et al. (2000) states that amplitude measurements should be taken at the same latency for different electrodes. If a peak is clearly maximal at one electrode location, its latency at this location should be used. For widely distributed peaks, the average latency at a set of electrodes may be used, or different components may be quantified at peak latencies of different electrodes (for example, P3a at frontal electrodes and P3b at parietal electrodes). When measuring peaks at different latencies for different electrodes, one cannot assume that they represent the same component (Donchin et al., 1978; Picton et al., 2000; Spencer et al., 2001). For example, a late positive wave found to target stimuli in an oddball task typically peaks earlier in frontal than parietal regions. Therefore, one can assume that the frontal P3 and parietal P3 reflect activation of anatomically distinct sources and distinct cognitive functions.

Although the peaks of a waveform provide a convenient point for measuring activity, they typically do not reflect unitary cerebral events. Therefore, measuring a peak at different latencies for each electrode site may be useful when attempting to investigate the phenomenology of the component, but it may confound investigations attempting to examine the neurophysiological processes underlying the scalp surface potential. The focus of this thesis is in elucidating the nature of stop-signal inhibition process, and is therefore, not concerned with examining the intrinsic variability of a peak's movement across the scalp, but rather, with the variability of a particular cognitive process across the scalp, as manifested in a component. Therefore, the scalp distribution of a component was examined at the point in time when summated activity was maximal.

## **2.5 ERP Overlap**

A fundamental issue in the measurement of ERPs time-locked to stop-signals is the contamination from activity related to the processing of the preceding primary task go stimulus. Because successful stop trials predominantly consist of shorter stop-signal delays and failed stop trials consist of longer delays, the relative degree of overlap from the preceding go stimulus will be markedly different for average ERPs on successful and failed trials, seriously confounding the comparability of these two trial-types. A similar problem exists between two conditions or groups that differ in average stop-signal delay. The following section briefly outlines the methods that have been used by previous stop-signal studies to correct this problem.

### 2.5.1 *The Subtraction Method*

The subtraction method involves subtracting ERP waveforms time-locked to the go stimulus for no-signal trials from stop-signal trials, and then re-aligning the waveform to the onset of the stop-signal (de Jong et al., 1990; Kok, Ramautar, de Ruiter, Band, & Ridderinkhof, 2004; Overtom et al., 2002; Ramautar et al., 2004). No-signal trials are divided into slow and fast Go RTs, corresponding to the successful and failed stop parts of the RT distribution, with the estimated  $n$ th RT (see section 1.6.1) used as the delineator. This technique works on the race model independent processes assumption that the RT distribution for stop-signal trials corresponds to the RT distribution for no-signal trials. Therefore, no-signal trials for slow RTs (i.e. corresponding to the successful stop part of the RT distribution) are subtracted from successful stop trials, while no-signal trials for fast RTs (i.e. corresponding to the failed stop part of the RT distribution) are subtracted from failed stop trials.

This method appears theoretically sound on face value as go stimulus processing that is common to no-signal and stop-signal trials is removed, with residual activity reflecting only processing of the stop-signal. However, there is a danger in the use of difference waveforms to isolate components, particularly between different trial-types within a task, as the residual activity may produce spurious components. Firstly, the assumption that go processing is similar for no-signal and stop-signal trials may not be a justified one, as shown by evidence suggesting that Go RT is prolonged in a stop-signal task compared to a typical choice-RT task (Rieger, 2000; van den Wildenberg et al., 2003). Secondly, no-signal trials consist of response processing, which is always accompanied by response-related negativity over central regions (Brunia & van Boxtel, 2000), while for successful stop trials, depending on where the stop-signal was presented, response processing is cut short. Therefore, these trials are accompanied by a



lack of, or considerably reduced, response-related negativity. The result of subtracting no-signal trials from successful stop trials would be a difference waveform showing response-related positivity. For example, this is evident in van Boxtel, van der Molen, Jennings and Brunia (2001), who found a large centrally-maximal P3 in the successful stop minus no-signal difference waveform, which displayed a lateralisation that was typical of a response-related component. More recently, van Boxtel (2003) suggests that it is better to quantify the amplitude of a component in the original waveforms.

In contrast, as both failed stop and no-signal trials contain response-related negativity, one may be justified in subtracting these trial-types. Nevertheless, caution needs to be taken when subtracting trials, to avoid introducing spurious response-related components, by ensuring that failed stop and no-signal trials are equated for RTs. Furthermore, van Boxtel et al. (2003) suggests that examining ERPs time-locked to the response minimises temporal differences between trials. The resultant difference waveform should reflect aspects of response-related, error processing (Ramautar et al., 2004; van Boxtel, 2003).

### 2.5.2 *Smearing*

This method is based on Woldorff's (1993) theory that randomly varying or "jittering" the inter-stimulus-interval around a mean value can partially cancel or smear out the effects of preceding stimulus ERP overlap. When sub-averages for each interval are averaged together to obtain a "Full Average", the overlapping adjacent responses tend to cancel each other out. The effect of the ISI jitter on the overlap from adjacent responses is similar to a low-pass filtering operation, diminishing the amount of overlap caused by long-latency ERP components to the preceding stimulus. This can be

conceptualised as the mutual cancellation of positive and negative values of the waveform and works much better for high than low frequency components. An empirical rule of thumb is that the effective jitter range needs to be larger than the period of the slowest dominant wave in the overlapping response (Woldorff, 1993).

This technique may be applied to stop-signal ERPs by calculating ERP averages for successful and failed stop trials at each of the stop-signal delay sub-ranges for each subject, and then collapsing the sub-averages together (Dimoska, Johnstone, Barry, & Clarke, 2003; Pliszka et al., 2000), thereby, equating the degree of go stimulus overlap between trials. Previous studies have jittered stop-signals in a 200 – 600 ms range (Pliszka et al., 2000) or 0 – 500 ms (Dimoska et al., 2003). The current thesis adopted this method to correct go stimulus overlap on stop-signal ERPs. Pre-stimulus baselines for the successful and failed stop “Full Average” ERPs are similar and flatter after this correction (see Appendix A).

### 2.5.3 *ADJAR Level-2 Technique*

Another method recently applied to correcting stop-signal ERPs is an extension of the “smearing” method, known as the ADJAR Level-2 technique, which involves estimating the overlap of the preceding and proceeding responses and subtracting this from the Full Average (Bekker, Kenemans, Hoeksma, Talsma, & Verbaten, 2005a; Bekker et al., submitted; see Woldorff, 1993 for details). This technique is most appropriate if the jitter range is not sufficient to remove overlap from Full Averages, if an examination of ERPs at each stop-signal delay are of interest, or finally, if the actual effect of the go stimulus on stop-signal processing is of interest (Woldorff, 1993). The reliability and validity of this method has not yet been examined.

## 2.6 Stop-signal Delays

Presenting stop-signals either closer or further away from the point of response execution influences the stage of response processing upon which inhibition acts. If subjects receive only short or long stop-signal delays,<sup>11</sup> average stop-signal ERPs may reflect differential inhibitory processing between subjects. One method of circumventing this problem is to present stop-signals at set intervals relative to a subject's expected MRT. For example, by presenting a stop-signal 100 ms prior to the expected MRT for all subjects, inhibition of a similar stage of "late" response processing is captured in each subject, regardless of what the actual MRT is. This provides an average ERP across stop-signal delays that reflects inhibition of response processing at similar stages along the response trajectory between subjects.

## 2.7 Stimulus-locked ERPs in the Stop-signal Task

Some mid-latency components such as the P50 "gating" response have shown evidence of sensory forms of inhibition (Croft, Dimoska, Gonzalez, & Clarke, 2004; Olincy et al., 2000), however, cognitive and motor forms of inhibition are more likely to manifest in the long latency components (i.e. between 50 and 1000 ms post stimulus onset). The following section reviews each auditory-evoked ERP component firstly in a general context and then more specifically in the stop-signal task, with a focus on the non-clinical adult population (but see Chapter 3 for a critical review of the functional role of each component).

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<sup>11</sup> This is a problem with the tracking method for setting stop-signal delays.

### 2.7.1 *The N1 Component*

The auditory N1 typically shows a maximum at the vertex, a peak latency ranging from 100 to 150 ms, and is evoked to sudden changes in the level of energy impinging on the sensory receptors in the auditory cortex (Näätänen & Picton, 1987). It is believed that N1 reflects a part of the auditory system that measures change and duration of auditory stimulation, monitoring trial-to-trial changes in sensory input, which may mediate the amount of attention that is switched towards a stimulus (Näätänen & Picton, 1987). N1 may be evoked to: (a) the onset of an auditory stimulus after an interval of silence, and (b) a change in pitch or intensity of a stimulus (i.e. a physical parameter), although the response is larger in the former context. Among other functions, the N1 is believed to reflect the initial extraction of information from the sensory analysis of the stimulus (Näätänen & Picton, 1987).

A large body of research shows that the N1 component is the result of multiple neural generators (e.g. Näätänen & Picton, 1987; Vaughan & Ritter, 1970). Specifically, there appear to be three distinct exogenous components underlying the early negativity, each with its own source, and each being affected differentially by stimulus features and state factors (i.e. arousal) (Näätänen & Picton, 1987). However, another broader fronto-central negative component has also been shown to overlap the N1 at 60 – 130 ms, and may extend for hundreds of milliseconds thereafter (Hillyard, Vogel, & Luck, 1998; Näätänen, 1982; Näätänen & Michie, 1979). Known as the *processing negativity* (PN) (Näätänen, 1982; Näätänen & Michie, 1979), or the *negative-difference wave* (Nd) in the attend minus unattend difference waveform (Hansen & Hillyard, 1988), this component appears to be modulated by attention and has been variably interpreted as reflecting a process that leads to preferential processing of sensory input through early stimulus set selection (Broadbent, 1970) using the

stimulus' physical attributes (Hillyard & Hansen, 1991; Hillyard, Hink, Schwent, & Picton, 1973; Hillyard et al., 1998), a matching process that compares physical attributes to a representation in memory (Näätänen, 1992; Näätänen & Michie, 1979), or finally, the modulation of perceptual sensitivity to incoming stimuli (Hillyard, 1981).

Within the stop-signal task, the auditory stop N1 has a fronto-central distribution and peaks approximately 100 to 130 ms after the onset of the stop-signal in adults (Bekker et al., 2005a; Bekker et al., submitted; de Jong et al., 1990). Source localisation has shown that the auditory stop N1 originates from the auditory cortex (Bekker et al., submitted). De Jong et al. (1990) found that N1 in the difference waveform (i.e. stop-signal minus no-signal trials) occurred with equal amplitude and latency for successful and failed stop trials, which they interpreted as support for the identification of this component as an exogenous N1 (Näätänen & Picton, 1987), reflecting the processing of the physical parameters of the stop-signal but not its associated task requirements. In ADJAR-corrected ERPs, stop N1 (80 to 120 ms) was larger for successful compared to failed stop trials, and this difference was greatest in the fronto-central region (Bekker et al., 2005a; Bekker et al., submitted). This effect was interpreted as reflecting a greater attentional switch towards the stop-signal on successful than failed trial that was determinative for the quality of subsequent inhibitory control (Bekker et al., 2005a; Bekker et al., submitted).

### 2.7.2 *The P2 Component*

Generally, the auditory P2 peaks approximately 150 to 250 ms after the onset of a stimulus, shows a central maximum (e.g. Melara, Rao, & Tong, 2002) and is believed to be generated in the adjacent auditory cortex (Oades, 1998). Functional interpretations of P2 have been inconsistent in the literature. Some researchers suggest

that P2 may reflect the inhibition of sensory input from further processing (Johnstone, 2001), with larger amplitude reflecting greater sensory inhibition (Melara et al., 2002). Others suggest that larger P2 amplitude reflects greater sensory processing, as an increase in P2 amplitude has been found with an increase in stimulus intensity in subjects with low central serotonergic activity who are unable to adjust individual levels of sensory processing (Hegerl & Juckel, 1993).

Within the stop-signal task, auditory stop-signals do not appear to elicit a clearly distinguishable P2 component in adults. An inspection of the grand average ERP waveforms typically shows a very small P2 at frontal sites that is barely distinguishable from the stop N2, with no evidence of a P2 at centro-parietal sites (see Figure 1, Bekker et al., 2005a, p. 193; see Figure 1, Bekker et al., submitted; see Figure 6, de Jong et al., 1990, p. 177). Although Bekker et al. (submitted) found a positivity that peaked at 220 ms after the onset of the stop-signal in the successful stop minus failed stop difference waveform, they called this component the stop P3. However, this positive component may have been the result of subtracting the N2-related activity on failed stop trials from successful stop trials, which contained no negativity at this latency range (van Boxtel, 2003). Therefore, the auditory stop P2 does not appear to occur in adults.

### 2.7.3 *The N2 Component*

The N2 is also believed to be made up of three different components: (a) the mismatch negativity that is automatically elicited to any deviance in auditory stimulus presentation, whether the stimulus is attended or not (Näätänen, 1995), (b) the centrally-maximal N2b, which is evoked to attended stimuli only (Coles & Rugg, 1995) and may reflect a controlled expectancy mismatch process (Näätänen & Picton, 1986), and (c) the N2c or “classification N2”, which is elicited only when the stimulus is a target

(Pritchard, Shappell, & Brandt, 1991). In the auditory oddball task, the N2 potential for standard (“nogo”) stimuli has been shown to decrease with increasing age (Enoki, Sanada, Yoshinaga, Oka, & et al., 1993; Johnstone, Barry, Anderson, & Coyle, 1996; Oades, Dittmann-Balcar, & Zerbin, 1997), becoming overlapped by the increase in activity of a positive component around the same latency. Larger auditory-evoked N2 amplitude in children may be consistent with a wider range of attention focus, with maturation allowing more focused processing (Friedman, Boltri, Vaughan, & Erlenmeyer-Kimling, 1985). Therefore, reduced N2 amplitude in adults may reflect conscious discriminatory processes being subsumed by earlier, more efficient and automatic, sensory discriminatory process, as reflected in the N1 (Johnstone, et al., 1996).

Within the stop-signal task, the auditory stop N2 in adults presents as a small negative component at fronto-central sites on the descending flank of the N1, peaking around 210 to 220 ms after the onset of the stop-signal (Bekker et al., 2005a, Figure 1, p. 193; Bekker et al., submitted, Figure 1). Although de Jong et al. (1990) did not report a stop N2 in the difference waveform, a small negativity is evident in the grand average ERPs for failed stop trials at the late stop-signal delay only (see Figure 6, p. 177). In contrast, the visual stop N2 in adults presents as a large, clearly distinguishable component. It has a lateral-frontal maximum and peaks at approximately 250 ms in the difference waveform (van Boxtel et al., 2001). However, a consistent characteristic of N2 across these studies is greater negativity for failed compared to successful stop trials (van Boxtel et al., 2001), with this effect largest in the central (Kok et al., 2004) or centro-parietal region (Ramautar et al., 2004). Source localisation shows that the failed stop N2 is associated with central activity, possibly reflecting a source in the anterior

temporal cortex (Kok et al., 2004). With respect to latency, N2 may peak later for failed compared to successful stop trials (Kok et al., 2004; Ramautar et al., 2004).

Although the auditory stop N2 has not been discussed in previous studies, the visual stop N2 has been interpreted as reflecting (a) a “central” inhibition process that is activated to a greater extent on failed than successful stop trials (van Boxtel et al., 2001), (b) “red-flag” inhibition process (Pliszka et al., 2000), and more recently (c) an evaluative process that represents monitoring for the erroneous response on failed stop trials (Kok et al., 2004; Ramautar et al., 2004; see section 3.5.1 for a detailed review of the function of N2).

#### 2.7.4 *The P3 Component*

There have been three P3 components identified in the general literature. (1) The “classic P3” (Donchin & Coles, 1988) or “P3b” (Squires, Squire, & Hillyard, 1975), which has a centro-parietal maximum, is evoked to attended stimuli when the stimulus requires classification into a category, and varies as an inverse function of the probability assigned to the category, as well as the extent to which the task is central to the subject (Duncan-Johnson & Donchin, 1977; Johnson & Donchin, 1978; Spencer et al., 2001; Squires, Wickens, Squires, & Donchin, 1976). The P3b has been associated with a mechanism that updates a model of the environment or context in working memory (Donchin, 1981; Donchin & Coles, 1988). (2) The “novelty P3”, elicited to (as the name suggests) novel, deviant stimuli that are attended to, but require no response. Although the component has a fronto-central distribution, its magnitude and latency are similar to the classic P3 (Courchesne, Hillyard, & Galambos, 1975). (3) The small “P3a”, which occurs whether a stimulus is attended or not with a fronto-central distribution (Squires et al., 1975). Spencer et al. (2001) states that the P3a is not a



separate component to the classic P3 and novelty P3, but rather, that it may reflect the contributions of both components. Due to the difficulty in dissociating the three components, and their inconsistent appearance, some researchers refer to these components and the anterior-negative, parietal-positive Slow-Wave collectively as the “Late Positive Complex” (LPC) (Spencer et al., 2001).

Within the stop-signal task, auditory stop P3 in adults shows a central maximum, peaks at 300 ms (Bekker et al., 2005a; Bekker et al., submitted; de Jong et al., 1990), and is larger in the frontal than parietal region (de Jong et al., 1990). Source localisation for successful stop P3 suggests a source in the medial fronto-central region that might reflect activity in the anterior cingulate cortex (ACC) (Bekker et al., submitted). However, the distribution of stop P3 appears to vary with the probability of the stop-signal. When stop-signals are presented on 20 % of trials, successful stop P3 shows a source in the frontal cortex (Ramautar et al., 2004), but a source near the midline-precentral cortex (i.e. near or in the motor or premotor cortex) when stop-signals are presented on 50 % of trials (Kok et al., 2004; Ramautar et al., 2004). In contrast, failed stop P3 has a centro-parietal maximum and a source located deeper (ventrally) in the central region than successful stop P3 when stop-signals were presented on 50 % of trials (Kok et al., 2004; Ramautar et al., 2004), and a source in lower parietal areas when stop-signals were presented on 20 % of trials (Ramautar et al., 2004). These findings suggest that failed stop P3 may reflect summated activity from widely distributed regions (Kok et al., 2004; Ramautar et al., 2004).

Typically, P3 amplitude shows larger amplitude for successful compared to failed trials, and this difference was largest in the central region (Bekker et al., submitted; de Jong et al., 1990), although others have found the converse effect (Kok et al., 2004). With respect to latency, stop P3 has been shown to peak later for failed

compared to successful stop trials (Bekker et al., 2005a; Bekker et al., submitted; Kok et al., 2004; Ramautar et al., 2004), which has been interpreted in line with the race model, whereby the late engagement of the inhibition process results in a failed stop (Logan & Cowan, 1984; Logan et al., 1984).

It has been suggested that P3 onset time corresponds to SSRT, when estimated relative to electromyography (EMG) onset time, rather than Go RT, reflecting the interval from stop-signal onset to the inhibition of muscle activity. This finding, and enhanced P3 amplitude for successful compared to failed trials, have suggested to some researchers that the stop P3 may reflect a general inhibitory effect on central response activation (de Jong et al., 1990). Kok et al. (2004) interpreted successful stop P3 as reflecting a stop-signal inhibition process located in or near the motor or premotor cortex. Others suggest that the onset of the stop P3 (~ 140 ms) occurs too late to reflect SSRT (~ 200 ms), due to the fact that there is a supposed transmission delay of approximately 100 ms from the onset of a process to its effect on performance measures (Bekker et al., submitted). Nevertheless, the different scalp distribution for P3 on successful and failed stop trials suggests that failed stop P3 may reflect a process other than inhibition. Specifically, it has been suggested that failed stop P3 may reflect processing of the erroneous response on failed stop trials (Kok et al., 2004).

### *2.7.5 Summary of Auditory Stop-signal ERPs in Adults*

The above review shows that, in adults, auditory stop-signals are associated with a large fronto-central N1/P3 complex and a small N2 on the descending flank of the N1, with P2 indistinguishable from N2. Auditory stop N1 has been interpreted as reflecting the amount of attention that is switched to a stimulus, with enhanced amplitude reflecting greater attention to the stop-signal that may be pertinent for subsequent

successful inhibition. The auditory stop N2 appears to be larger for failed compared to successful trials in the grand ERP averages, however, because of its small magnitude in adults, its functional role is unclear. Finally, the stop P3 is typically enhanced for successful compared to failed trials for auditory stop-signals, the converse effect for visual stop-signals, and has been generally associated with the stop-signal inhibition process on successful stop trials, although the exact nature of the association requires further investigation.

## **2.8 Response-locked ERPs in the Stop-signal Task**

### *2.8.1 Error-Negativity*

The Error-Negativity (Ne) (Falkenstein, Hohnsbein, & Hoorman, 1995a) or Error-related Negativity (ERN) (Gehring, 1992) is a negative component that is best observed when ERPs are time-locked to responses. Peaking at approximately 80 to 150 ms, with a fronto-central maximum, the Ne is evoked predominantly to erroneous responses, thus, suggesting a role in error processing (Gehring et al., 1993). An Ne-like component has also been observed to correct responses, although there is dispute as to whether this is in fact the Ne (Falkenstein et al., 2000). Brain imaging studies have shown Ne to be typically generated in the ACC, although there have been inconsistencies with respect to whether this activation occurs in the rostral (Garavan, Ross, Kaufman, & Stein, 2003; Menon, Adelman, White, Glover, & Reiss, 2001; Schall, Stuphorn, & Brown, 2002) or caudal region (Nieuwenhuis et al., 2003; van Veen & Carter, 2002).

Scheffers, Coles, Bernstein, Gehring, and Donchin (1996) found that both errors of choice (i.e. between response alternatives) and errors of action (i.e. failed stop on

trials requiring inhibition)<sup>12</sup> elicit an Ne of similar latency, amplitude and morphology. Enhanced Ne amplitude has been shown for faster errors (Gehring, Coles, Meyer, & Donchin, 1995; but see Falkenstein, Hoormann, Christ, & Hohnsbein, 2000 for an exception) and errors produced with less response force. Furthermore, Ne is greater preceding compensatory responses that slow RT for the proceeding trial and in subjects who adopt a more cautious response strategy of slow and accurate responding (Gehring et al., 1995; Pailing, Segalowitz, Dywan, & Davies, 2002). Amplitude, however, does not appear differ between high and low error groups (Falkenstein et al., 1999; Falkenstein et al., 2000). It has also been suggested that Ne may overlap and distort stimulus-locked components when RTs are fast (Hajcak, Vidal, & Simons, 2003).

Error-related theories suggest that Ne is elicited when a mismatch is detected between the “actual” response and a neural representation of the “intended” response (Falkenstein et al., 2000; Gehring et al., 1995). This has been supported by the finding that Ne is larger the greater the discrepancy between the intended and actual response (Bernstein, Schnur, Bernstein, Yeager, & et al., 1995a; Falkenstein et al., 2000). However, Nieuwenhuis, Ridderinkhof, Blom, Band, and Kok (2001) found that Ne could occur even without the subject’s conscious awareness of an error, suggesting that the Ne process has access to information that may not necessarily be available to conscious error monitoring. Some researchers suggest that Ne occurs too late to reflect the detection of error (Bernstein, Scheffers, & Coles, 1995b; Gehring & Fencsik, 1999), with studies showing evidence of correction of the erroneous response prior to the onset of the Ne (Gehring & Fencsik, 1999; Rodriguez-Fornells, Lorenzo-Seva, & Andres-Pueyo, 2002). Recently, researchers have put forward a theory of conflict-monitoring,

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<sup>12</sup> Responses on failed stop responses are not necessarily erroneous in the typical sense of the term because the response itself may correspond to the go stimulus. It is the presence of the stop-signal that makes the response inappropriate, and therefore, erroneous.

which suggests that the Ne is the result of a comparator process evaluating the degree of “conflict” in information processing (Carter et al., 1998; van Veen & Carter, 2002), rather than error.

Within the stop-signal task, Ne has rarely been investigated. Ramautar et al. (2004) found a double-peaked negative component for response-locked ERPs, which peaked at 80 and 100 ms, and was larger for failed stop compared to no-signal trials. In the response-locked difference waveform (i.e. failed stop minus no-signal trials), a single fronto-central negative peak occurred at 100 ms (Ne) (Ramautar et al., 2004). Van Boxtel (2003) found a source in the caudal aspect of the medial frontal region for stop Ne. The stop Ne has been interpreted in line with the traditional view that Ne reflects the detection of an error (van Boxtel, 2003).

### 2.8.2 *Error-Positivity*

In contrast to the Ne, the Pe has received less attention in the general literature. It has a centro-parietal maximum and peaks approximately 300 ms after the onset of the response (Nieuwenhuis et al., 2001). The Pe is very similar to the stimulus-locked “classic” P3 in morphology, polarity and scalp topography. As a result of this correspondence, some researchers suggest that the Pe is a second P3 component, elicited by the evaluation of the incorrect response (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Falkenstein et al., 2000). However, experimental manipulations have shown that the P3 and Pe are functionally distinct (Falkenstein et al., 2000). The Pe has been variably interpreted as reflecting (a) conscious error recognition (Band & Kok, 2000; Falkenstein et al., 2000), (b) adjustment of response strategies after an error, as evidenced by post-error slowing in RT (Falkenstein et al., 2000; Nieuwenhuis et al., 2001), or (c) the subjective and affective assessment of errors, as evidenced by a larger

Pe in subjects with a low compared to high frequency of errors, reflecting the increased emotional significance of the error (Falkenstein et al., 2000).

Within the stop-signal task, Ramautar et al. (2004) found a Pe component 300 ms after the onset of the overt response that was larger for failed stop compared to no-signal trials. In the response-locked difference waveform (i.e. failed stop minus no-signal trials) a centro-parietal positive peak was evident at 300 – 350 ms. Van Boxtel (2003) found a fronto-central Pe in the difference waveform, which had a source in the rostral aspect of the medial frontal region, while Pe in the original failed stop waveform had a parietal generator. The stop Pe has been interpreted generally as reflecting the evaluation of an error (van Boxtel, 2003).

## **2.9 Visual Primary Choice-RT Task ERPs in the Stop-signal Task**

Although it is not an aim of this thesis to examine ERPs to the primary choice-RT task, a brief review of previous investigations is provided.

In adults, N2 to go stimuli has a frontal maximum and peaks later for no-signal trials with slower compared to faster RTs (Ramautar et al., 2004). The parietally-maximal P3 to go stimuli appears to be larger in amplitude and peaks earlier for fast compared to slow RT no-signals trials, particularly in the parietal region (Ramautar et al., 2004). Furthermore, P3 amplitude to go stimuli was larger for failed compared to successful stop trials. It was suggested that a stronger bias towards responding to the primary task may be associated with an enhanced go P3, which may be more difficult to inhibit upon the presentation of a subsequent stop-signal (Ramautar et al., 2004).

In children, Brandeis et al. (1998) examined microstates (i.e. the degree and spread of activation at a particular fixed latency) for successful and failed stop trials time-locked to the go stimulus. They found a larger P2/N2 microstate to go stimuli for

failed compared to successful stop trials, which they interpreted as reflecting the efficient engagement of attention to the go stimulus, which resulted in faster response execution, and ultimately a failed stop. Similarly, Pliszka et al. (2000) found a slow positive wave to go stimuli that was maximal over the right frontal scalp and larger in amplitude for failed compared to successful stop trials, which was interpreted in line with Brandeis et al. (1998).

These effects suggest that the manner in which go stimuli are processed may affect the subsequent inhibitory outcome. However, ERPs to go stimuli reflect not only response preparation and activation, but also processes related to stimulus discrimination in a choice RT task. In contrast, the lateralised readiness potential (LRP) is an electrophysiological index that reflects motor-related processes specifically related to the preparation of a left or right hand response, but which eliminates other processes. The following section provides a review of the LRP and its previous utility in the stop-signal task.

## **2.10 Lateralised Readiness Potential**

### *2.10.1 General*

Preceding an overt hand movement, a gradually increasing negative potential has been recorded from the scalp beginning 1 s or more prior to movement onset (Kornhuber & Deecke, 1965). This negative, ramp-like potential is known as the “readiness potential” (RP) and is equally large over both hemispheres at the start of the rise, but begins to lateralise before the response and is larger over the scalp contralateral to the response-side. The lateralisation of this component reflects the differential involvement of the left and right motor cortices in preparing to execute unimanual

motor acts (Kutas & Donchin, 1980), such that the onset of the lateralisation reflects the point in time where the response side is determined. However, motor-related lateralised potentials can be overlapped by lateralised potentials related to other structural and functional differences between the hemispheres. Therefore, the difference in total lateralisation between left and right hand responses is typically utilised to derive the lateralised readiness potential (LRP) (Coles, 1989; Kutas & Donchin, 1980).

The LRP is believed to be generated in the precentral and primary motor cortices due to findings showing that activation of cells in the motor cortex closely parallels the onset and time course of the LRP (Band & van Boxtel, 1999; Coles, 1989), and that EMG activity appears to begin when the LRP reaches a fixed threshold value, regardless of the actual response latency or accuracy (Gratton, Coles, Sirevaag, & Donchin, 1988; but see Band & van Boxtel, 1999 for a critical review). As the onset of the LRP reflects the point in time that a left or right hand response was selectively prepared and the onset of motor outflow (Coles, 1989; Kutas & Donchin, 1980), the intervals preceding and succeeding the onset can provide an insight into the duration of pre- and post-motor processes, receptively (Hsieh & Yen-Ting, 2003; Leuthold, 2003; Osman & Moorer, 1993).

Previous studies have found that nogo stimuli in the go/nogo task show partial LRPs, which have been interpreted as reflecting sub-threshold response activation in the motor cortex (Miller, Riehle, & Requin, 1992). Specifically, the LRP for nogo stimuli was shown to start approximately 250 ms after the stimulus and appeared to be “cut-off” at 500 ms, which suggested that preliminary sensory information started response activation 250 ms after the onset of the stimulus, but then other sensory attributes extinguished response activation 250 ms later (Miller et al., 1992; Osman, Moorer, & Ulrich, 2003). These findings are consistent with the notion that an inhibition signal



which arrives at the primary motor cortex attenuates motor outflow, reflected in the reduction of LRP amplitude (e.g. de Jong et al., 1990). Therefore, the LRP may be used to examine the effect of response activation and inhibition processes. However, because LRP amplitude reflects the balance between response activation and inhibition processes in the motor cortex (Band et al., 2003a), the concurrent contribution of these two processes cannot be disentangled. For example, reduced LRP amplitude in one condition relative to another may be due to greater inhibition acting on response processes, or to inefficient response activation.

#### *2.10.2 Estimating LRP Onset*

As estimating the duration of pre- and post-motor processes can provide a powerful method for determining the locus of experimental effects, the LRP onset must be accurately identified. Mordkoff and Gianaros (2000) compared a number of LRP onset scoring methods and recommended that the  $1df$  regression-based procedure (SSIDF in their terminology) be used to analyse stimulus- and response-locked LRP data.<sup>13</sup> The regression-based procedure defines the onset of the LRP as the point of intersection between two linear regression lines: a pre-onset and post-onset line (Schwarzenau, Falkenstein, Hoorman, & Hohnsbein, 1998). The subtypes of this method differ in terms of degrees of freedom ( $df$ ) that are afforded the two regression lines during the fitting procedure.

In contrast, the criterion-based method identifies the onset of the LRP by finding the first point in time that the LRP waveform exceeds some criterion, which may be

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<sup>13</sup> Mordkoff and Gianaros (2000) compared the regression-based procedure with the criterion method (Smulders, Kenemans, & Kok, 1996) and the baseline-deviation method (Osman & Moorer, 1993). The latter is not discussed in this thesis.

arbitrary or defined as a certain portion of the peak amplitude value (Smulders et al., 1996). This method is easy to use but suffers some problems. For example, early trends in the waveform, preceding LRP onset, in the negative direction may result in an earlier point being chosen as the onset, while a trend in the opposite direction may result in the onset being chosen too late. Different slopes of the rising flank of the LRP can also affect estimated onset using the criterion method. Two waveforms may possess the same onset, although due to faster response preparation or execution latency, one slope may be steeper than the other. This scenario would result in an earlier estimated onset for the steeper waveform (see Chapter 7 and Appendix B for a comparison of the regression and criterion methods).

## **2.11 Chapter Summary and Aims**

The above focused review of ERPs in the stop-signal task revealed a few common threads running through stop-signal studies. Firstly, almost all investigations of inhibition using the stop-signal task employed the simple form of inhibitory response (see section 1.7.2). There appears to be a serious deficiency of investigations comparing ERPs in the simple stop-signal task with ERPs from more complicated versions of stopping (see Chapter 5), and with alternative inhibition tasks (see Chapter 4). Secondly, successful and failed stop trials were associated with the activation of distinct neural networks, as evidenced by the scalp distributions of ERP components and dipole source modelling. Attempts to isolate processing related to the success and failure of inhibition may provide further insight into the differential functional roles of ERP components within stop-signal processing (see Chapter 6). Thirdly, stop-signal probability differed between studies, which may account for some of the differences in

scalp distribution of ERP components (see Chapter 7). These issues are further explored in the following chapter.

### **3. The Stop-signal Inhibition Process**

#### **3.1 Chapter Aims**

The aims of this chapter are to draw together the relevant literature on inhibitory processing across tasks and measures. Specifically, this chapter: (a) outlines current neuropsychological models of response activation and inhibition, (b) examines the functional significance of electrophysiological indices of response inhibition, and (c) reviews literature related to examinations of the nature of stop-signal inhibition through a comparison with other forms of inhibition and manipulating the difficulty or complexity of inhibition.

#### **3.2 The Triad of Inhibition**

In order to understand the nature of response inhibition, one must first consider the vital distinction made by Band and van Boxtel (1999) between the “agent”, “site” and “manifestation” of inhibition. Adopting this approach serves to clarify a number of conceptual discrepancies within the inhibition literature. The agent (i.e. source) of inhibition is the brain process responsible for the decision to inhibit or the process that releases the inhibition signal. This is different from the process at which inhibition is exerted (i.e. the site). Therefore, the site is where the inhibition and response processes “meet” (Band & van Boxtel, 1999; Logan, 1994). Furthermore, the agent and site of inhibition can be inferred using measurements of the reduction of the response (i.e. the manifestation).

It is possible that these three aspects of inhibition may occur at the same time and location, but it is more likely that the site and manifestation of inhibition occur at

some point after the actual agent of inhibition. Band and van Boxtel (1999) suggest that, assuming inhibitory control works in a “top-down” manner as suggested by Logan and Cowan (1984), the agent of inhibition at site A may release an inhibition signal that acts on subsidiary processes at site B, although a reduction in activity may not manifest until site C. Specifically in relation to the examination of ERPs, it should be maintained that ERP components identified reflect the activation of underlying neural processes, and that these may reflect activity related to the agent, site or manifestation of inhibition.

### **3.3 Neuropsychological Models of Response Activation and Inhibition**

The following section provides an outline of the current neuropsychological models of response activation and inhibition, as they pertain to the inhibition of a motor hand response.

#### *3.3.1 A Model of Response Activation*

Goldberg (1985) proposed that the selection and preparation of a motor response follows two neural “loops”. See Figure 3.1, adapted from Band and van Boxtel (1999, p. 184), which depicts the circuits involved in the generation of a motor response in a schematic diagram. The first (medial) loop consists of wide-spread regions of the cerebral cortex that project to the basal ganglia and motor nuclei of the thalamus, and then back to the supplementary motor area (SMA), functioning as an integrated network in the specification of response parameters and the selection of responses (Band & van Boxtel, 1999). The motor-related RP is believed to be generated during this loop. Once the response parameters have been programmed, Bullock and Grossberg (1988) suggest

that the *force* of the movement is enhanced by the basal ganglia and that the GO-signal is released from the primary motor cortex to the peripheral structures. The second (lateral) loop proposed by Goldberg (1985) includes activity from the motor, somatosensory and parietal association areas, which project via the thalamus and cerebellum back to the premotor and primary motor cortex. The lateral loop is vital because it adjusts the response parameters of the first loop in line with contextual information to improve the timing and smoothness of actions (Band & van Boxtel, 1999; Goldberg, 1985). Furthermore, the LRP is believed to be generated during this loop.

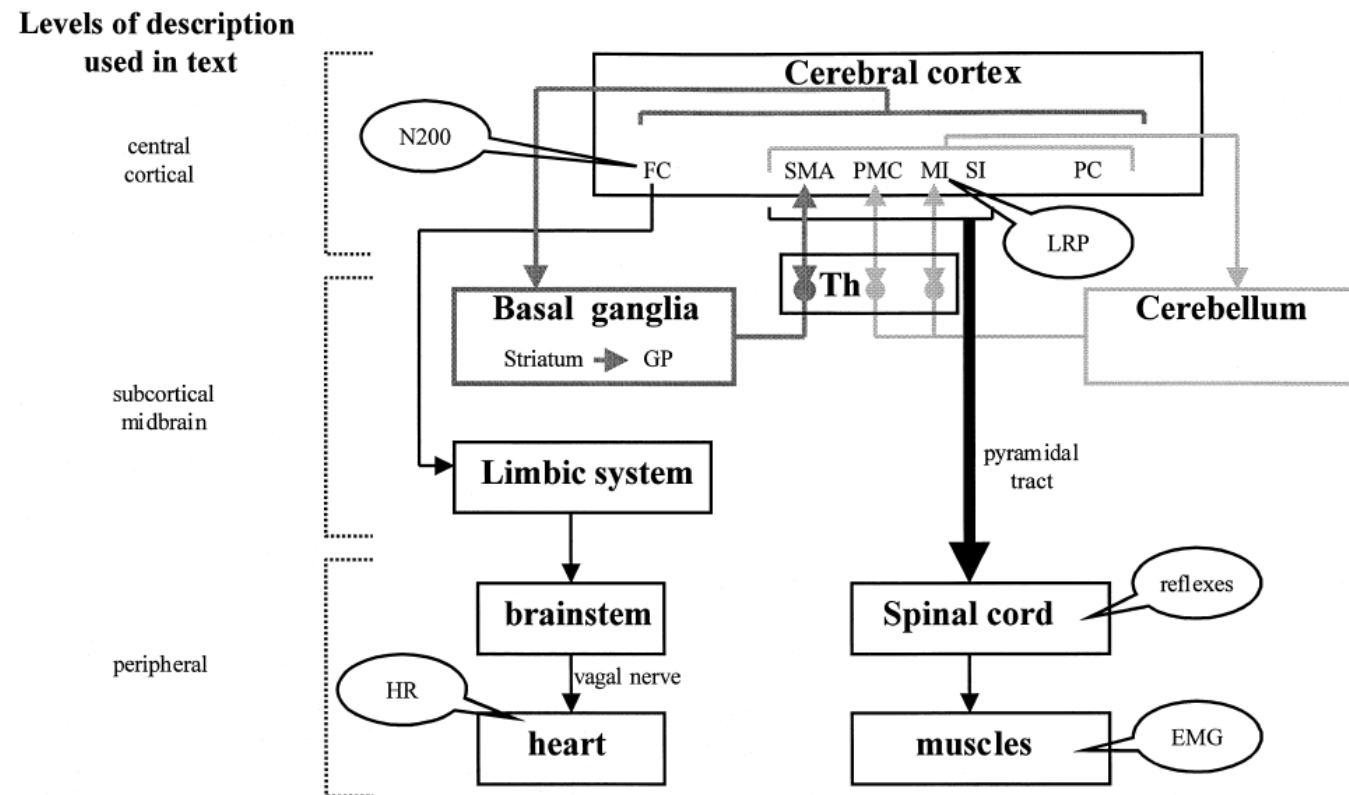
### 3.3.2 *Frontal-Subcortical Inhibition System*

Band and van Boxtel (1999) proposed an account of response inhibition that attempts to integrate response activation (Goldberg, 1985) and inhibition (Brunia, 1993), due to the belief that the activation and inhibition pathways meet each other at the “site” of inhibition (see Figure 3.1). Firstly, they suggest that the agent of inhibition is localised “upstream” from the primary motor cortex, along the central nervous system (CNS). The PFC and the basal ganglia, in particular the globus pallidus, are implicated as candidate agents for inhibition in the stop-signal task, with the PFC acting as the higher-order centre modulating subcortical input to the motor cortex by “gating” the thalamic transmission of the activity from the basal ganglia and cerebellum (Band & van Boxtel, 1999; Brunia, 1993). According to Brunia (1993), the thalamic gate must be open for a go-signal to be processed through the primary motor cortex, while an active closing of this gate reflects response inhibition. The last site of inhibition is believed to be the primary motor cortex (Band & van Boxtel, 1999) and possibly the somatosensory cortex (van Boxtel & Band, 2000). Brunia (1997) suggested two

possible routes along which response inhibition can be realised. The slow route involves the modulation of basal ganglia activity through an excitatory influence on the subthalamic nucleus, resulting in an attenuation of input to the motor cortex. This notion was supported by van den Wildenberg (2003) who found that stimulation of the subthalamic nucleus significantly improved response inhibition.

The fast route involves the PFC activating the thalamic reticular nucleus, resulting in a reduction of thalamo-cortical communication (Band & van Boxtel, 1999). More recently Brunia (2003) suggested that the shortest cortical pathway that response inhibition in the stop-signal task could be realised through was from the SMA to inhibitory interneurons in the spinal cord. See Brunia (2003) for a more detailed review of the potential mechanisms and neural pathways of inhibition.

Therefore, response inhibition appears to involve a network consisting of the PFC in conjunction with the (a) basal ganglia, and (b) primary motor regions, via subthalamic nuclei. This is consistent with Logan and Cowan (1984) in that response inhibition is exerted by a higher-order centre that stops the support for lower-order processes involved in the go response.



**Figure 3.1.** Schematicised diagram from Band and van Boxtel (1999, Figure 1, p 184) showing the medial and lateral loops involved in response activation and inhibition (Goldberg, 1985). Notes: (1) the callouts contain the psychophysiological measures reflecting the activity of the structure they are believed to be associated with as per Band and van Boxtel (1999); (2) FC = frontal cortex; GP = globus pallidus; MI = primary motor cortex; PC = parietal cortex; PMC = premotor cortex; SI = somatosensory cortex; SMA = supplementary motor area; Th = thalamus



### 3.3.3 *Two-Mechanism<sup>14</sup> Model of Inhibition*

De Jong et al. (1995) suggests that response inhibition is achieved through more than one process. Examining the LRP, de Jong and colleagues (1990) found activity on some successful stop trials at the middle and late stop-signal delays, which exceeded the “threshold” value associated with typical responding. “Supra-threshold” LRP activity suggested to these researchers that the go response was being stopped after it had left the primary motor cortex; they, therefore, proposed the existence of an inhibition mechanism that operates “downstream” from the cortex, in the CNS. They suggested the midbrain may be a potential location for this “peripheral” mechanism, which subjects evoked when responses had to be stopped in an “all-or-none” manner. The peripheral mechanism was believed to inhibit the transmission of motor output from cortical to peripheral motor structures (Bullock & Grossberg, 1988). However, some researchers argue for a site of inhibition right up to the point of the spinal cord motoneurons (McGarry, Chua, & Franks, 2003; McGarry & Franks, 2000, 2003).

The “central” cortical mechanism of inhibition was believed to manifest in the successful stop P3 and in the reduction of LRP activity. Successful stop P3 was interpreted as reflecting the inhibition of unspecific response activity, while the reduction of LRP amplitude was interpreted as reflecting the inhibition of side-specific response activity. The similar timing of these two separate manifestations of cortical inhibition were interpreted as a “general inhibitory effect on central response activation processes” (de Jong et al., 1990, p. 178).<sup>15</sup> Although central inhibition was believed to be utilised in all inhibitory situations, de Jong et al. (1995) suggested that it was

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<sup>14</sup> The term “mechanism” refers to the processes by which certain actions are affected and is sometimes used in place of the term “process”.

<sup>15</sup> Although de Jong et al. (1990) states that the P3 and LRP amplitude reduction reflect two distinct manifestations of central inhibition they refer to them in the global sense as a “central inhibition mechanism”.

predominantly used when inhibition had to be “selectively” evoked, such as in the stop-change task, where the stop-signal indicates the inhibition of one go response but the concurrent activation of an alternate go response.

This theory was supported by Jennings, van der Molen, Brock, and Somsen (1992) who found that vagal inhibition, believed to be mediated by the midbrain, occurred concurrently with successful inhibition of motor responses in the simple stop-signal task. However, the theory has been challenged by the fronto-subcortical model outlined above, which states that a single agent of inhibition can account for suprathreshold LRP activity. That is, while the agent of inhibition is fixed, the site of inhibition may differ along the response processing trajectory (Band & van Boxtel, 1999; van Boxtel et al., 2001). Van Boxtel et al. (2001) found that LRP remained above threshold for a shorter duration on partial compared to failed stop trials, which they interpreted as support for the existence of a single inhibitory mechanism that becomes effective at different instants during response activation. In line with the response maintenance hypothesis, they suggested that response activation continues only whilst there is support from higher processes (Band & van Boxtel, 1999; Logan & Burkell, 1986; van Boxtel et al., 2001).

### 3.3.4 *The Inhibitory Role of the Prefrontal Cortex*

A meta-analysis of neuroimaging studies suggests a localisation of response inhibition across diverse cognitive tasks to a network of PFC regions: bilateral dorsolateral PFC, inferior frontal cortex (IFC) and the dorsal ACC, but not other frontal regions (Duncan & Own, 2000). Yet, the precise location of response inhibition within the PFC has proven to be difficult to localise (Duncan & Own, 2000).

Inhibition of a motor response appears to activate the inferior frontal gyrus (IFG) on nogo trials in the go/nogo task (Konishi et al., 1999; Menon et al., 2001) and stop-signal trials (Rubia et al., 1999; Rubia et al., 2001). Aron, Fletcher, Bullmore, Sahakian, and Robbins (2003b) correlated SSRT with different PFC regions and found a significant positive relationship with damage to the right IFG, in particular the pars opercularis, and to a smaller extent with the medial frontal region (although this relationship was accounted for by IFG). In contrast, left lobe damage in the corresponding regions did not show the same relationships, indicating a stop-signal inhibition-specificity to the right hemisphere. Sasaki, Gemba, and Tsujimoto (1989) found that electrical stimulation of the PFC foci in the monkey, including the principal sulcus and rostroventral corner, reduced electrical activity in the motor cortex, a region that is anterior to the IFG. The human analogue of this region is the middle frontal gyrus (Kaufer & Lewis, 1999).

Most researchers suggest that the extensive connectivity of the different regions of the PFC with other lobes and sub-cortical regions argues for a dynamic view of response inhibition that involves all regions of the brain (e.g. Robbins, 1998). For example, the pre-SMA and rostral ACC have reciprocal anatomical connections with lateral PFC and parietal brain regions and both these areas have been shown to be involved in the inhibition of motor responses, as shown through brain imaging (Garavan, Ross, Murphy, Roche, & Stein, 2002; Rubia, Smith, Brammer, & Taylor, 2003), electrophysiology (Brandeis et al., 1998; Naito & Matsumura, 1996) and lesion data (Drew, 1975). However, the PFC may not be specifically associated with inhibitory control per se, as it may be more generally associated with the selection (Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000; Rubia et al., 2003) or

switching of responses (Garavan et al., 2000), among other executive functions (Miller & Cohen, 2001; Pennington, 1996; Roberts & Pennington, 1996).

While these findings provide an insight into the involvement of particular brain structures during performance of inhibition tasks, they do not disentangle processes specifically related to inhibition, as distinct from other processes involved in task performance. Most brain imaging studies lack the temporal sensitivity to separate sensory-perceptual processes from further, higher-order, central processes. In contrast, ERPs provide excellent temporal information about the individual stages of processing.

### **3.4 Electrophysiological Indices of Inhibition**

In order to investigate the nature of the stop-signal inhibition process, its electrophysiological correlate must be known. The following section provides a comprehensive, critical review of current functional interpretations of N2, P3 and other electrophysiological indices that have been associated with response inhibition across the inhibition literature.

#### *3.4.1 The Functional Role of the Inhibition-related N2*

##### **3.4.1.1 The Inhibition Hypothesis**

The N2 is a negative component that has been quantified as early as 170 ms after auditory nogo stimuli (e.g. Falkenstein, Hoormann, & Hohnsbein, 2002) and as late as 300 – 400 ms after visual stimuli (e.g. Kok, 1986). The N2 typically shows larger amplitude for nogo compared to go trials in the go/nogo task (see Banquet, 1981 for an exception), and displays a frontal (e.g. Kiefer, Marzinzik, Weisbrod, Scherg, & Spitzer, 1998) or fronto-central maximum (e.g. Pfefferbaum & Ford, 1988; Pfefferbaum et al.,

1985), which has led to its interpretation as reflecting a frontal inhibition process (e.g. Kok, 1986). Variations of the inhibition hypothesis include that the N2 reflects: (a) a “red flag” signalling the need for inhibition (Kok, 1986),<sup>16</sup> (b) the detection or inhibition of an inappropriate tendency to respond (Kopp, Mattler, Goertz, & Rist, 1996), (c) a pre-motor, modality-specific inhibition process (Falkenstein et al., 1999, 2002), (d) the agent of inhibition itself (van Boxtel et al., 2001), (e) the switch to a response inhibition mode (Swainson et al., 2003), and (f) within the selective stop-signal task, the final site of inhibition (Naito & Matsumura, 1996).

Support in favour of N2 reflecting, at least, a frontal process comes from brain imaging studies and dipole source modelling. The N2 has shown sources in the bilateral inferior PFC (Kiefer et al., 1998), the right PFC (Swainson et al., 2003), the caudal ACC (Bekker, Kenemans, & Verbaten, 2005b; Nieuwenhuis et al., 2003; Van Veen & Carter, 2002), as well as showing combined activity in the dorsolateral PFC and caudal ACC (Mathalon, Whitfield, & Ford, 2003), predominantly in the right hemisphere (Bokura, 2001). Furthermore, the N2 has been associated with the pre-SMA (Naito & Matsumura, 1996), an area known to be involved in the initiation and inhibition of motor responses.

Support in favour of the inhibition hypothesis was established with the finding that N2 was larger for nogo compared to go trials for both overt and covert responses, albeit to a lesser degree for the latter type, suggesting that the effect was not due to motor-related negativity on go trials, but to the activation of inhibition on nogo trials (Bruin & Wijers, 2002; Pfefferbaum et al., 1985). Furthermore, enhanced N2 amplitude for nogo trials has been shown even when stimulus probabilities are equal (Eimer, 1993;

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<sup>16</sup> It should be noted that Kok (1986) identified an N400 component in one experiment and an N480 component in a second experiment, which he interpreted as reflecting a “red flag” process, and suggested that they were equivalent to the N2 component found in visual discrimination tasks.

Jodo & Kayama, 1992; Schröger, 1993), ruling out oddball-type differential attention effects.

Some researchers have pointed out that the comparison of go and nogo trials is fraught with problems because of the differences inherent between these trials. For example, go trials contain motor-related activity whereas nogo trials do not. Furthermore, it has been suggested that go and nogo trials may differ in attentional requirements (Kopp et al., 1996). To circumvent these issues, the specific priming go/nogo or flanker tasks have been used where a cue specifically primes the subject for a left or right hand go response, or a nogo response, and on some trials the target stimulus that follows is incongruent to the cue. These studies have shown mixed results with some reporting larger N2 amplitude for nogo trials that were specifically primed for a left or right hand response (Kopp et al., 1996), presumably reflecting greater inhibitory activation, relative to nogo trials primed for a nogo response. Others have found no difference between trials, mainly because an N2 was evoked to all nogo trials, even though subjects had been primed for a nogo response, and there was no evidence of response preparation on these trials, as shown by a lack of LRP development (Bruin, Wijers, & van Staveren, 2001). This suggests that N2 may not be associated with the active inhibition of a response.

The examination of N2 in children with ADHD typically shows reduced amplitude, which has been interpreted as either contributing to a slower inhibitory response (Dimoska et al., 2003), or as reflecting an under-active right-frontal inhibition process (Pliszka et al., 2000). However, N2 may be modality-specific in adults (e.g. Johnstone et al., 1996), with greater amplitude for visual compared to auditory stimuli, despite greater inhibitory performance through the latter modality (Falkenstein et al., 1999; Falkenstein et al., 1995b). Falkenstein et al. (1995b) interpreted this to mean that

N2 reflects response inhibition in the visual modality only. They expanded this interpretation in a later study, suggesting that the N2 reflects a modality-specific inhibition process that works on inhibiting responses at a pre-motor level (Falkenstein et al., 1999). Kiefer et al. (1998) suggests that auditory N2 is small on the scalp surface because of the overlap of a positive component in the fronto-central region. In contrast, it has been suggested that the reduced perceptual overlap of different auditory stimuli makes them easier to discriminate from each other, relative to visual stimuli, resulting in smaller N2 amplitude (Nieuwenhuis, Yeung, & Cohen, 2004). However, this latter interpretation is congruent with a number of functional interpretations for N2. Therefore, in adults, although N2 appears to reflect response inhibition in the visual modality, in the auditory modality, this association is dubious.

#### **3.4.1.2 The Response Conflict Hypothesis**

More recently in the go/nogo literature, researchers are suggesting an evaluative, rather than executive, role for the N2. Some believe that N2 on correct inhibition trials reflects the detection of conflict between concurrently activated responses by the caudal ACC (Carter et al., 1998; van Veen & Carter, 2002). According to the response conflict theory, “conflict” occurs because on nogo trials the correct nogo inhibitory response attempts to override the initially prepared and prepotent go response (Kopp et al., 1996; Nieuwenhuis et al., 2003; Van Veen & Carter, 2002). When the nogo inhibitory response successfully overrides the go response, the conflict generated by the concurrent activation of these responses occurs early and is relatively minimal, as reflected in the stimulus-locked N2. However, on trials where the inhibition process fails to stop the go response, both go and nogo responses are maximally activated at the

point of the overt response, thus, manifesting in the response-locked Ne component (Falkenstein et al., 2000; Gehring, Goss, Coles, Meyer, & Donchin, 1993).

According to the response conflict theory, the stimulus-locked N2 on successful stop trials and the response-locked Ne on failed stop trials are separate manifestations of the same process, with a temporal dissociation between successful and failed stop trials, and greater activation on the latter trial type. However, examinations of the relationship between N2 and Ne has shown conflicting results. Some researchers suggest they reflect the same process, with similar scalp distribution and dipole source modeling showing activation in the caudal ACC (Bekker et al., 2005b; Nieuwenhuis et al., 2003; van Veen & Carter, 2002). However, Falkenstein et al. (1999) compared nogo N2 and Ne and found that, while N2 was affected by stimulus modality and differed between poor and good inhibitors, Ne did not vary similarly. Furthermore, the components differed in topography, with Ne displaying a more central maximum compared to the frontally-maximal N2. Mathalon et al. (2003) found that nogo N2 was associated with activity in the dorsolateral PFC and the caudal ACC, arguing that N2 reflects the aggregate activity of both response inhibition and response conflict.

A prediction of the response conflict hypothesis is that low frequency responses are associated with greater response conflict when in competition with a prepotent response (Nieuwenhuis et al., 2003; Van Veen & Carter, 2002). In line with this prediction, researchers have found larger N2 amplitude for low compared to high frequency stimuli, regardless of whether the stimulus required a response or inhibition of that response (Donkers & van Boxtel, 2004; Nieuwenhuis et al., 2003). However, these studies do not seem to consider the confounding effects of stimulus probability, whereby the N2b, a sub-component of the N2 (see section 2.7.3), evoked to stimulus deviance, shows an inverse relationship with stimulus probability (Pritchard et al.,



1991) (see Chapter 7 for an investigation into the effects of stimulus probability on stop-signal ERPs).

Together these findings suggest that the stop N2 may reflect response inhibition or response conflict, and may become enhanced to novel, salient stimuli.

### 3.4.2 *The Functional Role of the Inhibition-related P3*

#### **3.4.2.1 The Inhibition Hypothesis**

The P3 is a positive component that peaks around 300 – 500 ms after the onset of a nogo stimulus (e.g. Falkenstein et al., 1999, 2002) and appears to be modality-independent (Tekok-Kilic, 2001). P3 typically shows larger amplitude for nogo compared to go trials in the go/nogo task and has displayed a frontal (Bruin & Wijers, 2002), fronto-central (Eimer, 1993; Kok, 1986; Roberts, Rau, Lutzenberger, & Birbaumer, 1994) or central (Banquet, 1981; Simson, Vaughan, & Ritter, 1977) maximum. The *nogo-antriorisation effect* is the finding that P3 amplitude has a more anterior distribution for nogo compared to go trials (Fallgatter & Strik, 1999).

Earlier reports suggested that the difference in scalp distribution between go and nogo trials reflected the differential overlap of other potentials over an underlying “unitary P3” (Hillyard, Courchesne, Krauz, & Picton, 1976). Using a PCA, Pfefferbaum et al. (1985) found that there were no other components overlapping the nogo P3. In contrast, Falkenstein et al. (1995b) suggested that the P3 was comprised of two components that overlapped differentially for go and nogo trials, suggesting the activation of similar processes. However, it is currently accepted that the different scalp distribution of P3 for go and nogo trials reflects the activation of distinct underlying neural generators (Johnson, 1993; Pfefferbaum & Ford, 1988; Spencer et al., 2001).

Distinct neural generators for go and nogo trials are supported by evidence from dipole source modelling, which shows that the go P3 has generators in the bilateral temporal junction (Kiehl, Smith, Hare, & Liddle, 2000; Menon et al., 2001), while nogo P3 has generators in the left premotor or motor cortex (Kiefer et al., 1998), left orbitofrontal cortex (Bokura, 2001), pre-SMA and ACC (Swainson et al., 2003). These findings are consistent with the frontal midline source derived for the successful stop P3 when stop-signals were presented on 20 % (Ramautar et al., 2004) or 40 % of trials (Bekker et al., submitted), and the midline-precentral source when stop-signals were presented on 50 % of trials (Kok et al., 2004). Therefore, findings suggest that the inhibition-related P3 involves generators in the ACC and motor-related areas.

Nogo P3 has been invariably associated with response inhibition (e.g. Birbaumer, Elbert, Canavan, & Rockstroh, 1990; Fallgatter & Strik, 1999; Kiefer et al., 1998; Strik, Fallgatter, Brandeis, & Pascual-Marqui, 1998; Tekok-Kilic, 2001), while go P3 has been related to target detection and evaluation (Eimer, 1993; Pfefferbaum et al., 1985), or the update of contextual information in working memory (Donchin & Coles, 1988). Other researchers suggest that larger P3 amplitude for nogo compared to go trials is due to the resolution of the motor-related, contingent negative variation (CNV) component on nogo trials, in contrast to go trials, where motor-related activity results in larger negative amplitude (Kok, 1986; Kopp et al., 1996; Simson et al., 1977). However, enhanced P3 amplitude for nogo trials has been found to occur for both covert, as well as, overt responses suggesting that motor-related activity cannot fully account for the effect (Bruin & Wijers, 2002; Pfefferbaum & Ford, 1988). Furthermore, the effect has been found to remain even after the subtraction of preparatory motor-related activity (Roberts et al., 1994), and even when stimulus probabilities are equal (Eimer, 1993; Jodo & Kayama, 1992; Schröger, 1993), ruling out oddball-type effects.

Investigations into the function of the inhibition-related P3 are sparse compared to investigations into N2. As outlined in section 2.7.4, within the stop-signal task, successful stop P3 has been interpreted as reflecting a general (non response side-specific) cortical inhibition process for auditory stop-signals (de Jong et al., 1990) and the actual stop-signal inhibition process for visual stop-signals in adults (Kok et al., 2004; Ramautar et al., 2004) and in children (Overtom et al., 2002). When Falkenstein et al. (1999) compared poor and good inhibitors in a go/nogo task, P3 did not differ between groups, which they interpreted as evidence against an inhibition role. However, in a later study, these researchers suggested that the nogo P3 reflects a general, modality-nonspecific, inhibition process (Falkenstein et al., 2002). Within priming studies, P3 has been found to be larger for nogo trials that had been specifically primed for a left or right hand response, compared to non-specifically primed nogo trials (Bruin et al., 2001). Furthermore, Bruin et al. (2001) found no evidence of a P3 on nogo trials which had been specifically primed for a nogo response and showed no evidence of response preparation (i.e. no LRP activity). This suggests that P3 may be directly related to the inhibition of response activation. Other researchers, however, have found the P3 to be unaffected by priming (Kopp et al., 1996).

Clinical studies have shown that P3 amplitude is reduced in children with ADHD, corresponding to a slower SSRT and reduced inhibition probability in the stop-signal task (Overtom et al., 2002), however, when inhibition probability was equated between groups, stop P3 does not appear to differ between ADHD and control groups (Dimoska et al., 2003). Therefore, in children, P3 may be related more to the success or outcome of inhibition, than to a process governing the latency of the inhibitory response (Dimoska et al., 2003). Furthermore, it has been suggested that P3 peaks too late to reflect the inhibition of a response (Falkenstein et al., 1999; Naito & Matsumura, 1996),

which is typically estimated to have a latency of 200 to 250 ms in non-clinical adults (Logan, 1994). Naito and Matsumura (1996) put forth that P3 may reflect the termination of the inhibition process, itself reflected in the N2.

Therefore, the above review shows that P3 has been generally related to response inhibition (e.g. Bruin et al., 2001; Kiefer et al., 1998) with variations of the inhibition hypothesis including: (a) a general (non response side-specific) cortical inhibition process (de Jong et al., 1990; Falkenstein et al., 2002), (b) the stop-signal inhibition process itself, (c) the outcome of inhibition, and (e) the termination of the inhibition process in frontal motor-related areas (Naito & Matsumura, 1996).

#### **3.4.2.2 Alternative Hypotheses**

Alternative hypotheses have been put forth which are not entirely inconsistent with the inhibition hypothesis, but provide a broader consideration of other factors such as cortical arousal.

Karlin and Martz (1973) examined P3 amplitude for rare and frequent stimuli in conditions where the response was either required immediately following a cue, or after the presentation of a second target stimulus. They found that P3 amplitude was larger when the response set had be changed from the prepotent to rare response, but only when there was an urgency to change sets. In contrast, in the delayed response conditions, when the response set could be changed more leisurely, P3 amplitude was much smaller. They interpreted this effect to mean that the P3 may reflect a phasic arousal response, where it is the need to urgently change response sets that develops greater arousal. Under this interpretation, P3 does not reflect the inhibition of the prepotent response, but rather, the arousal associated with this task. In contrast, Banquet (1981) suggested that P3 may be related to the inhibition of arousal. They

found larger P3 amplitude in a second compared to a first experimental session in a go/nogo task and suggested that the arousal reaction, which follows a decision, was inhibited to a greater extent in the second session.

Therefore, these hypotheses suggest that P3 may be related to general cortical arousal: either the arousal response itself (Karlin & Martz, 1973), or the inhibition of that response (Banquet, 1981).

### *3.4.3 Earlier Components and Inhibition*

As the latency of the inhibitory response is typically 200 – 250 ms in young, non-clinical adults, one may logically expect that the decision to inhibit a response would occur prior to the development of the N2. Naito and Matsumura (1996) examined the effect of stop-signal inhibition by examining EMG data, and found the reduction of motor activity occurred 140 ms after the stop-signal. They interpreted this to suggest that some other inhibition process may operate prior to the process reflected in the N2. Similarly, in the go/nogo task, Filipovic, Jahanshani, and Rothwell (2000) suggested that larger N1 amplitude for nogo compared to go trials, which preceded EMG activity, may index the pre-motor decision to either execute or not prepare a go response. Furthermore, Bekker et al. (2005a) found larger N1 amplitude for successful compared to failed stop trials and suggested that this effect may reflect a greater attentional switch to the stop-signal that is determinative for subsequent successful inhibition.

Using depth-electrodes in monkeys, Sasaki et al. (1989) found a negative potential around 110 – 150 ms after a nogo stimulus in the bilateral principal sulcus. Although this potential has often been equated with the nogo N2 in humans (e.g. Kok 1986), its latency appears to correspond better with the N1. Furthermore, Sasaki,

Gemba, Nambu, and Matsuzaki (1993) used magnetoencephalography (MEG) in humans and found a deflection approximately 110 – 170 ms after the onset of the nogo stimulus in the left fronto-parietal region, which they interpreted as the inhibition-related nogo potential. Together, these findings show evidence of inhibition-related activity as early as 100 ms after the inhibition stimulus.

#### 3.4.4 *Summary: ERP Indices of Stop-signal Inhibition*

The above review shows that the N2 has been broadly interpreted as being related to response inhibition; either the decision associated with triggering an inhibition response, the agent of inhibition, and even the site of inhibition. However, more recently, N2 has been associated with an evaluative process in the ACC that detects response conflict. In contrast, although there has been some debate over the effect of CNV resolution on nogo trials, the P3 has been generally interpreted as reflecting response inhibition, and in the stop-signal task, as the mechanism itself. Therefore, it appears that there is greater debate over the functional role of the N2, particularly in the auditory modality, with more certainty over the role of the P3. However, this may also be due to the fact that there are a greater number of studies that have focussed on explicating the function of the N2 in inhibition tasks. Nevertheless, particularly within the stop-signal task, it appears that the P3 may be a better index of response inhibition. Earlier inhibitory effects must be also considered within the N1 latency range.

### 3.5 **Examining the Psychophysiological Nature of Stop-signal Inhibition**

The following section reviews literature related to psychophysiological and brain imaging investigations of the nature of stop-signal inhibition through: (a) a

comparison of stop-signal inhibition with nogo inhibition, (b) a comparison of simple and selective inhibition, (c) a manipulation of stimulus probability, and (d) with consideration of the effect of response style on inhibition processes and strategies.

### *3.5.1 Stop-signal and Nogo Inhibition*

Comparative investigations of stop-signal inhibition with other forms of inhibition, particularly those that consider underlying brain mechanisms, are few in number. It is important to examine inhibitory processing differences between tasks as interpretations of ERP components for nogo trials have often been used to explain stop-signal ERP effects. However, the tasks appear to differ in a number of respects (see section 1.9).

Using fMRI, in a direct comparison of stop-signal and nogo inhibition, Rubia et al. (2001) found common areas of activation in the medial, middle and inferior frontal and parietal lobes. Specific activation was found during stop-signal task performance which included the medial PFC and predominantly right hemispheric activity in the ACC, SMA, inferior prefrontal and parietal areas. In contrast, inhibition in the go/nogo task activated a bilateral, although predominantly left hemispheric, middle-infero-mesio-frontal and parietal network. Between tasks, nogo inhibition showed increased activity in a left fronto-parietal network, which was interpreted as reflecting the activation of a response selection system. In contrast, the stop-signal task showed increased activity in a right homologue network. Therefore, nogo and stop-signal inhibition appear to be associated with the activation of distinct inhibitory networks, in particular, displaying a left versus right hemispheric dissociation.

Evidence of a left-hemispheric specialisation for nogo inhibition has also been found in ERP studies, particularly in the frontal region (Kiefer et al., 1998; Kok, 1986).

Roberts et al. (1994) found that a left-frontal maximum for the visual nogo P3 remained even after the subtraction of the CNV. This effect was interpreted as reflecting a lateralised positivity for nogo trials that was associated with response inhibition. Kiefer et al. (1998), using dipole source modelling, reported a source in the left precentral region for nogo P3, while others have found a source in the left orbitofrontal cortex (Bokura, 2001). However, not all studies agree with a left hemispheric dominance for nogo inhibition. Using fMRI, some researchers have localised nogo inhibition to the right prefrontal region (Casey, Castellanos, Giedd, & Marsh, 1997; Garavan, Ross, & Stein, 1999; Konishi et al., 1999). Due to the poor temporal resolution of fMRI, however, it is unclear whether these areas reflect inhibitory processing, or whether they reflect other processes related to task performance.

A right hemispheric specialisation has been supported for stop-signal inhibition through findings showing a correlation between the right inferior frontal cortex and SSRT (Aron, Robbins, & Poldrack, 2004; Aron et al., 2003b). In adults, the only ERP study to examine the lateral sites was van Boxtel et al. (2001), and this was restricted to the N2 component in the frontal region, which showed greater amplitude in the lateral sites compared to the midline. Therefore, there is no ERP evidence to support or discount a right hemispheric specialisation of stop-signal inhibition in adults.

An examination of activity between the go/nogo and stop-signal tasks across the sagittal region also suggests distinct differences that may be associated with the activation of task-specific inhibition processes. A review of the nogo and stop-signal literature (section 3.5.2) shows that the P3, which has consistently been associated with response inhibition in both tasks, shows a more fronto-central distribution for nogo trials (Eimer, 1993; Kok, 1986; Roberts et al., 1994) compared to the central (Bekker et al., 2005a; Bekker et al., submitted; de Jong et al., 1990) or centro-parietal (Kok et al.,



2004) maximum for successful stop trials. This suggests that nogo inhibition may involve a more frontally-based process while stop-signal inhibition may involve a centrally-located process. However, no study has directly compared P3 between nogo and successful stop trials.

Van Boxtel et al. (2001) examined ERPs in a combined visual go/nogo and stop-signal task, measuring nogo N2 at a latency of 350 ms and successful stop N2 at a latency of 250 ms. A comparison revealed a similar magnitude and lateral maximum in the frontal region between the two components. An examination of centro-parietal sites was not included. Although they interpreted this pattern of findings as reflecting the activation of a similar inhibition process for nogo and stop-signal inhibition, the actual functional role of N2 within stop-signal processing is still under debate in adults, particularly in the auditory modality (see section 3.5.1). Furthermore, although not reported, a small nogo N2 at a latency of 250 ms can also be observed in the waveforms (see Figure 5, van Boxtel et al. 2001, p. 252), showing greatly reduced amplitude relative to N2 for stop-signals.

Nogo N2 was also reported as peaking later for nogo stimuli compared to stop-signals, and this latency difference was interpreted as reflecting the additional time taken to process a greater number of stimulus parameters for a nogo stimulus (van Boxtel et al., 2001). That is, both direction and colour change of an arrow for the nogo stimulus, as opposed to only a colour change for the stop-signal. While the P3 component was not reported, an examination of the waveforms shows larger amplitude for nogo compared to successful stop trials (see Figure 5, van Boxtel et al. 2001, p. 252). These findings imply important processing differences between nogo and stop-signal inhibition, with inhibition potentially being evoked earlier after the inhibition stimulus in the stop-signal task.

One potential problem when combining nogo and stop-signal trials within the same task is that nogo trials may promote a reduced readiness to respond (van den Wildenberg et al., 2003; van den Wildenberg et al., 2002), which may lead to the activation of a different inhibition process than the urgent inhibitory “brake” typically used in the stop-signal task. Furthermore, it may cause problems for the race model’s assumption of stochastically independent response and inhibition processes (Logan, 1994). Therefore, a comparison of nogo and stop-signal trials *between* tasks, rather than *within*, may provide a more accurate account of the electrophysiological differences between the inhibition a prepared response and the inhibition of an ongoing response (see Chapter 4).

The above review suggests that nogo and stop-signal inhibition may be associated with the activation of distinct inhibitory networks, which may show a hemispheric dissociation. Furthermore, ERP findings suggest that nogo inhibition may be associated with the activation of a more frontal inhibition process, compared to the centrally-located process for stop-signal inhibition. Finally, the additional categorical stimulus discrimination in the go/nogo task has been shown to delay processing for nogo trials compared to stop-signals, suggesting later activation of the inhibition process. The above review, however, shows but a few direct comparisons of processing in the go/nogo and stop-signal tasks. Therefore, Chapter 4 of this thesis examines ERP differences between the cued go/nogo and simple stop-signal tasks, and in particular, determines whether nogo and stop-signal inhibition are associated with the activation of the similar or distinct inhibition processes.

### 3.5.2 *Simple and Selective (Stop/No-stop) Inhibition*

As mentioned above, the stimulus discrimination in the go/nogo task may delay processing. Similarly, the effect of stimulus discrimination on the inhibitory response has also been examined within the context of the stop-signal task. As outlined in section 1.7.2, complicating the stop-signal inhibitory response in this manner is believed to be associated with a slow, local mode of inhibition as opposed to a fast, global model for simple inhibition. This notion developed as a result of the finding of slower SSRT in the selective compared to simple stop-signal task (Bedard et al., 2002; Bedard et al., 2003; Riegler, 1986 as cited in Logan, 1994). However, two inhibitory modes do not necessarily imply two different inhibition processes (van Boxtel et al., 2001).

De Jong et al. (1995) examined the LRP in the simple and selective stop-signal tasks, as well as the stop-change task to determine whether the peripheral or central inhibition mechanisms may be evoked differentially between tasks. They found supra-threshold LRP activity for successful stop trials in the simple and selective stop-signal tasks, although SSRT was longer in the selective task. In contrast, LRP amplitude remained sub-threshold for successful stop trials in the stop-change task. They interpreted these findings as indicating the use of the same fast-acting, peripheral mechanism in the simple and selective stop-signal tasks, with inhibition merely being evoked later in the selective task, once primary task stimulus discrimination was complete. The central inhibition mechanism was believed to be utilised for the stop-change task because of the need to selectively inhibit one motor program while allowing the concurrent execution of another.

While de Jong et al.'s (1995) findings suggest a non-cortical inhibition mechanism was employed in the simple and selective stop-signal tasks, it is now widely accepted that the decision to inhibit (i.e. the agent) is located cortically (Band & van

Boxtel, 1999; van Boxtel et al., 2001). The fact that responses on some successful stop trials in the simple and selective conditions were inhibited after they were released from the primary motor cortex may indicate that the site of inhibition was similar between conditions, but this does not necessarily apply to the agent of inhibition. Therefore, these findings do not provide any insight into the actual inhibition process and the effect that the additional stimulus discrimination had on stop-signal processing. Furthermore, this study examined selective inhibition by asking subjects to discriminate between primary task stimuli, rather than between stop-signals. There is no study, to-date, which has examined the electrophysiology of response inhibition when stimulus discrimination is included in the response to the stop-signal.<sup>17</sup> This serious deficiency in the inhibition literature spurred the investigation in Chapter 5, which provides the first within-subject comparison of simple and selective stopping, using an examination of ERPs evoked to stop-signals for successful and failed stop trials, to determine the effect of an additional auditory stimulus discrimination on stop-signal inhibitory processing and strategies.

### 3.5.3 *Varying Stimulus Probability*

There is a well-documented history of stimulus probability affecting ERP component amplitude. In particular, N2 and P3 amplitudes have shown inverse relationships with an increase in stimulus probability in the oddball (e.g. Duncan-Johnson & Donchin, 1977) and go/nogo tasks (e.g. Banquet, 1981). These findings

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<sup>17</sup> The authors acknowledge Naito and Matsumura (1996) examined the electrophysiology of inhibition using a selective form of stop-signal task. However, the design of the stop-signal task precludes a meaningful interpretation of results with respect to selective stopping. For example, only one stop-signal delay (400 ms) was used in the task, which created a high degree of stop-signal expectation, as reflected in the very high inhibition probability. Furthermore, subjects were only instructed to “prepare” and not actually “execute” a response to the first stimulus, making the task more like a cued go/nogo than stop-signal task.

suggest a so-called “oddball effect”, where a rare stimulus evokes a greater cortical response merely because it is novel within the prevailing stimulus context (Duncan-Johnson & Donchin, 1977). It has also been suggested that reducing the probability of a nogo stimulus or stop-signal increases the bias towards responding, and thereby, increases the requirement for inhibitory processes (Ramautar et al., 2004; van den Wildenberg et al., 2003; van den Wildenberg et al., 2002) or the degree of response conflict (Donkers & van Boxtel, 2004; Nieuwenhuis et al., 2003).

There is only one stop-signal task study that has examined the effects of varying stop-signal probability on ERP components. Ramautar et al. (2004) examined ERPs time-locked to the go stimulus, the stop-signal and responses in 20 and 50 % probability conditions. Go stimulus-locked ERPs showed a frontal N2 that was larger and peaked earlier in the 50 than 20 % condition, with the converse effect found for P3 amplitude. The latter finding was interpreted as reflecting a greater bias towards responding when stop-signals were presented less frequently. Stop-signal ERPs showed a frontal N2 that was larger in the 20 than 50 % condition for successful stop trials, with the converse effect for failed stop trials. Similarly, a centro-parietal P3 was larger and peaked later in the 20 than 50 % condition across trials, although the amplitude effect was larger for failed stop trials. Greater N2 and P3 amplitudes for the 20 % compared to 50 % condition were interpreted as reflecting greater inhibitory activation to counteract the larger bias towards responding in this condition, while longer P3 peak latency for rare stop-signals was believed to reflect the greater difficulty in switching from a go response bias to an inhibitory requirement. Response-locked ERPs were also examined in an attempt to further elucidate the function of N2/P3 on failed stop trials. They found that although Ne was not affected by stop-signal probability, Pe was larger in the 20 than 50 % condition, which they suggested may be due to failed inhibitions for rare

stop-signals being perceived as more meaningful. However, the effect may have also reflected the greater number of failed inhibitions in the 20 % condition.

Effects of stimulus probability on early components have been shown in the go/nogo task for the visual P2, but not for the visual N1, with larger amplitude for rare compared to frequent stimuli (Czigler, Csibra, & Ambro, 1996). Stimulus probability effects in the auditory modality for these components have not been reported. With respect to later components, the N2 is typically larger for less probable stimuli across modalities, and regardless of response assigned to the stimulus (Banquet, 1981; Bruin & Wijers, 2002; Czigler et al., 1996; Donkers & van Boxtel, 2004; Nieuwenhuis et al., 2003). Nevertheless, enhanced N2 amplitude for rare compared to frequent stimuli is typically larger for nogo than go stimuli, suggesting the presence of two components (Eimer, 1993; Nieuwenhuis et al., 2003). This notion is further supported when the topographic distribution of N2 is considered. When stimulus probability is equal, the difference in N2 amplitude between nogo compared to go trials is localised to the frontal region (Bruin et al., 2001; Eimer, 1993; Falkenstein et al., 1999; Jodo & Kayama, 1992; Kok, 1986; Pfefferbaum et al., 1985; Schröger, 1993; Tekok-Kilic, 2001), but when nogo stimuli are rare, the effect is more profuse across the scalp (Eimer, 1993). Therefore, one N2 component may be affected by stimulus probability with diffuse activation across the scalp, while the other may be affected by the differential go or nogo response assignment and is localised to the frontal region (Eimer, 1993).

The P3 has also shown oddball-type effects independent of stimulus modality and stimulus type (Banquet, 1981; Bruin & Wijers, 2002; Czigler et al., 1996). Specifically, it has been suggested that P3 amplitude varies with the subject's subjective probability of event (Duncan-Johnson & Donchin, 1977). Furthermore, the topographic

distribution of the nogo P3 has shown a central maximum for rare nogo stimuli, and a centro-parietal maximum for equiprobable nogo stimuli (Pfefferbaum & Ford, 1988). In contrast, the topography of go P3 in the go/nogo task does not appear to vary with stimulus probability (Pfefferbaum & Ford, 1988), although P3 to target go stimuli in the oddball task show a shift to the central region with more probable stimuli (Duncan-Johnson & Donchin, 1977). In addition, Banquet (1981) dissociated the P3a and P3b (Squires et al., 1977; Squires et al., 1975), finding that the latter component was more sensitive to global stimulus probability, reflecting greater extraction of sensory information from rarer events.

In summary, some researchers suggest that larger N2 and P3 amplitudes when the probability of a nogo stimulus or stop-signal is reduced may reflect greater inhibitory activation in response to a greater bias towards responding. Concurrent probability effects for go stimuli in the oddball or go/nogo tasks argues towards an explanation in line with the oddball effect. It is clear that previous inhibition studies have been unable to dissociate true inhibitory processing differences from stimulus probability differences. Therefore, Chapter 7 explores this issue by using the selective stop-signal task to examine whether probability affects the stop-signal differentially than the ignore-signal, thereby reflecting inhibitory processing effects, over and above, the oddball effect.

#### *3.5.4 The Effect of Response Styles and Strategies*

Differing performance strategies may lead to differential activation of response inhibition processes as subjects with slower responses will obviously find it easier to inhibit a response than subjects with faster responses, who may require greater inhibitory activation, faster inhibitory activation, or both. For example, nogo N2 has

shown an increase in amplitude with an increase in time pressure, relative to the baseline (Jodo & Kayama, 1992) or relative to the peak of the preceding positive component (Band et al., 2003a). These findings have been interpreted as reflecting the greater recruitment of inhibition processes because fast responses are more difficult to inhibit and are associated with a greater likelihood of a failed stop. In contrast, Falkenstein et al. (1999) found larger N2 in a group of “good” inhibitors (greater inhibition probability) who showed slower RTs, relative to a group of “poor” inhibitors (reduced inhibition probability) who showed fast RTs. Therefore, in this later study, N2 amplitude was larger in the group that showed a greater control over the response process (i.e. by slowing responses), as opposed to, greater activation of the inhibition process.

With respect to P3, although not reported, an examination of the waveforms in Band et al. (2003a, Figures 3 and 9, pp. 272 and 275, respectively) show large, clear differences in P3 amplitude between conditions varying in response speed instructions. Nogo P3 was larger when response speed was emphasised relative to a balanced instruction, where both speed and accuracy were emphasised (see Figure 3, p. 272). Furthermore, P3 amplitude was larger for change trials in a change-response task when speed was emphasised, relative to the balanced instruction. These effects suggest P3 amplitude reflects the degree of inhibitory activation, which increases with the increased requirement for inhibition. In contrast, Falkenstein et al. (1999) did not find any differences between “good” and “poor” groups for P3 amplitude.

Using fMRI in a go/nogo task, Garavan et al. (2002) examined areas of activation on nogo trials that proceeded go trials with a fast or slow response. Following the inhibition of slow responses, they found that the dorsolateral PFC showed the greatest activation, whilst inhibition following a fast response was associated with



greater activation of the ACC. It was suggested that the dorsolateral PFC may act as a response selection process that subjects evoke when the inhibitory response can be chosen deliberately, prior to the go response being triggered in the primary motor cortex, while the ACC may be utilised in situations where there is an urgency to stop the response (Garavan et al., 2002). Kelly et al. (2004) expanded on this to show that the activation of these functionally distinct inhibitory networks was dependent upon the “degree” of response preparation, rather than the “speed” of the response, with an increase in ACC activity related to an increase in the degree of response preparation. These findings correspond with Casey et al. (1997) who found greater ACC activation in subjects who found it more difficult to inhibit responses in a go/nogo task, compared to greater activation of the orbito PFC in subjects who had less difficulty with response inhibition.

Therefore, adopting a particular fast or slow response style in the stop-signal task may determine the type of process or strategy used to stop that response. Furthermore, the use of different inhibition processes and strategies may be reflected differentially in the N2 and P3 components. Chapter 6 examines the effect that adopting a fast versus slow response style may have on inhibition processes and strategies.

### **3.6 Chapter Summary and Aims of Thesis**

The review of literature shows that there are but a few ERP investigations of stop-signal inhibition. However, what is immediately apparent from this review is that: (a) the functional significance of stop-signal ERPs is relatively unknown as there has been little attempt to dissociate processing on successful and failed stop trials, and the relationship between stop-signal ERPs and ERPs from other inhibition tasks,

particularly the go/nogo task, has been assumed; (b) although there has been some attempt to consider the stop-signal inhibition process in other (more complicated) inhibitory designs, there have been no studies examining ERPs reflecting the stop-signal inhibitory response in these contexts; (c) more generally, there has been little research that has examined the effect of within-subject manipulations on inhibitory processing, and (d) finally, the role of response styles and strategies has not been considered, although it is understood that individual differences in stopping can affect performance and underlying inhibitory processes.

In response to these issues, the primary aims of Part A of this thesis (Studies I – IV, Chapter 4 - 7) are to provide an insight into the nature of the inhibition process in the stop-signal task and, concurrently, attempt to elucidate the functional roles of stop-signal ERPs.

## 4. Study I - A comparison of event-related potentials in the go/nogo and stop-signal tasks

### 4.1 Abstract

The present study examined ERPs in an auditory cued go/nogo task and a typical stop-signal task with auditory stop-signals. Adults aged 18 to 39 years completed the two tasks, which included 30 % nogo trials and 30 % stop-signal trials, respectively. N1, N2 and P3 showed larger amplitudes for nogo compared to go trials, while in the stop-signal task, N2 was enhanced for failed compared to successful trials. A comparison between tasks suggested that inhibition was considerably more difficult in the stop-signal than go/nogo task, as evidenced by reduced inhibition probability. Successful stop trials were associated with larger amplitude and shorter peak latencies for all components, relative to correct nogo trials, suggesting earlier and greater activation of inhibitory processing. Topographic analyses revealed that nogo P3 had a frontal maximum and was lateralised to the left hemisphere, which was interpreted as reflecting a response selection network. Successful stop trials showed a centro-parietal P3 which was maximal at the midline, in line with suggestions of a stop-signal inhibition process in or near the motor or premotor cortex. However, these latter findings were interpreted as reflecting the *manifestation* of inhibition acting on different stages of response processing in the go/nogo and stop-signal tasks, rather than separate *agents* of inhibition.

## 4.2 Introduction

As outlined in section 1.9, the go/nogo and stop-signal tasks differ in: (a) the stage of processing at which inhibition stops the go response (Rubia et al., 2001), and (b) the manner in which inhibition is evoked. With respect to the first difference, responses in the go/nogo task may be stopped relatively early during response preparation, while responses in the stop-signal task may be stopped at variable stages of response processing, from preparation, up to the point of actual execution. As a consequence, inhibiting responses in the stop-signal task may be a more difficult task than inhibiting responses in the go/nogo task, and therefore, require greater inhibitory activation. Furthermore, inhibition in the cued go/nogo task is dependent upon the categorical stimulus discrimination of the nogo stimulus from the go stimulus, while in the typical stop-signal task, inhibition may be evoked as soon as the auditory stimulus is detected (i.e. complete stimulus identification may not be mandatory). Delayed inhibitory processing is supported by van Boxtel et al.'s (2001) finding that N2 peaked later for nogo compared to stop-signal trials. However, none of these differences have been explicitly examined in literature.

It has also been suggested that nogo and stop-signal tasks involve different inhibitory networks (Rubia et al., 2001). With respect to ERPs, distinct inhibition processes should manifest in different scalp distribution for ERPs between tasks. In particular, P3 appears to have a frontal or fronto-central distribution for nogo trials, but a central (de Jong et al., 1990; Ramautar et al., 2004) or centro-parietal (Kok et al., 2004) distribution for successful stop trials, suggesting differential inhibitory processing. Using fMRI, Rubia et al. (2001) found that nogo inhibition was associated with a left fronto-parietal network, while stop-signal inhibition was associated with a right homologue network, showing a left versus right hemispheric dissociation between

the tasks. As outlined in section 3.6.1, a left-hemispheric specialisation for nogo inhibition has also been found for nogo P3. Due to the fact that the predominant number of stop-signal ERP studies has focussed only on the midline sites, it is unclear whether the stop P3 may show a right-hemispheric dominance for stop-signal inhibition.

In summary, the primary objective of the present study was to provide a between-task ERP comparison of nogo and stop-signal inhibition. Due to the fact that responses are typically already triggered in the stop-signal task before inhibition is instructed, it was expected that inhibition would be more difficult in the stop-signal compared to go/nogo task, as evidenced by reduced inhibition probability. With respect to ERPs, the review of previous literature suggested that: (1) processing may be delayed for nogo compared to stop-signal trials because of the additional stimulus discrimination, resulting in longer peak latencies, (2) the P3 component may display a frontal inhibitory distribution for nogo trials and a central inhibitory distribution for stop-signal trials, and (3) nogo and stop-signal inhibition may be associated with hemispherically-distinct inhibitory systems. Finally, go/nogo and successful/failed stop effects were examined to determine whether previous findings could be replicated in the present study.

## **4.3 Method**

### *4.3.1 Subjects*

Thirty-five adults (19 males) aged 18 years 8 months to 39 years 11 months (mean age = 24.4 years, SD = 6.5 years) participated in this study as a requirement for an undergraduate psychology course. Subjects were included if they had a standardised score greater than 85 on the Standard Progressive Matrices test (SPM; Raven, 2000)

(mean = 117.0, SD = 15.5), never suffered an epileptic seizure, serious head injury, period of unconsciousness or any psychiatric condition. Each subject reported no problems with hearing, had normal or corrected-to-normal vision and were right-handed. Informed consent was obtained from all subjects after the testing equipment had been explained, with the option to withdraw without penalty.<sup>18</sup>

#### 4.3.2 *Procedure*

Subjects began by completing the SPM (Raven, 2000) and an information sheet used to screen for stimulant use, handedness and history of health concerns. In the laboratory, each subject was familiarised with the testing equipment and procedure. After equipment fitting, subjects were seated in a sound-attenuated testing room where they completed the go/nogo and stop-signal tasks, with task presentation counterbalanced between subjects. Time was taken to ensure that instructions were well understood.

#### 4.3.3 *Cued Go/Nogo Task*

Stimuli for the auditory cued go/nogo task were 1100 and 2000 Hz tones, presented binaurally at 60 dB SPL, with a 10 ms rise and fall time, through headphones. Stimuli were presented for 200 ms with a fixed inter-stimulus-interval (ISI) of 1300 ms. Each trial consisted of the presentation of one of the two tones, which either required a response (go) or the withholding of a response (nogo). After an initial

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<sup>18</sup> The experimental protocols for all the studies in thesis were approved by the joint University of Wollongong/Illawarra Area Health Service Human Research Ethics Committee.

practice block of 20 stimuli (50% nogo probability), two experimental blocks each consisting of 140 stimuli (30% nogo probability) were completed, with 1 – 2 minute breaks between blocks. Subjects responded by making a button press (*Ctrl* key on a standard keyboard) with the index finger of their right hand.

Subjects were given examples of the two stimuli and instructed to press the keyboard button quickly and accurately when they heard the go tone and withhold the button press when they heard the nogo tone. Stimulus-response assignment of tones was counterbalanced between subjects.

#### 4.3.4 Simple Stop-signal Task

The stop-signal task consisted of a primary, binary choice-RT task where visual go stimuli, consisting of cartoon pictures of a lion or an apple (3 cm high x 2 cm wide), were presented at eye-level, sequentially, in the center of a 14 in. computer monitor at a viewing distance of 1 m. Each trial lasted 2500 ms, consisting of a central fixation cross for 500 ms followed by the go stimulus for 2000 ms, allowing subjects 1500 ms to respond (see Figure 4.1). Digits II and III of the right hand were used to respond by pressing one of two buttons on a computer keyboard, which were marked with the words *apple* (Alt key) and *lion* (Ctrl key).<sup>19</sup> The stopping component of the task consisted of presenting a 1500 Hz tone, termed the stop-signal, on 30 % of trials, which instructed subjects to inhibit their response to the primary task (see Figure 4.1). Tones were presented binaurally over headphones for 100 ms (rise and fall time 10 ms), at an intensity of 60 dB SPL, and occurred an equal number of times for each go stimulus.

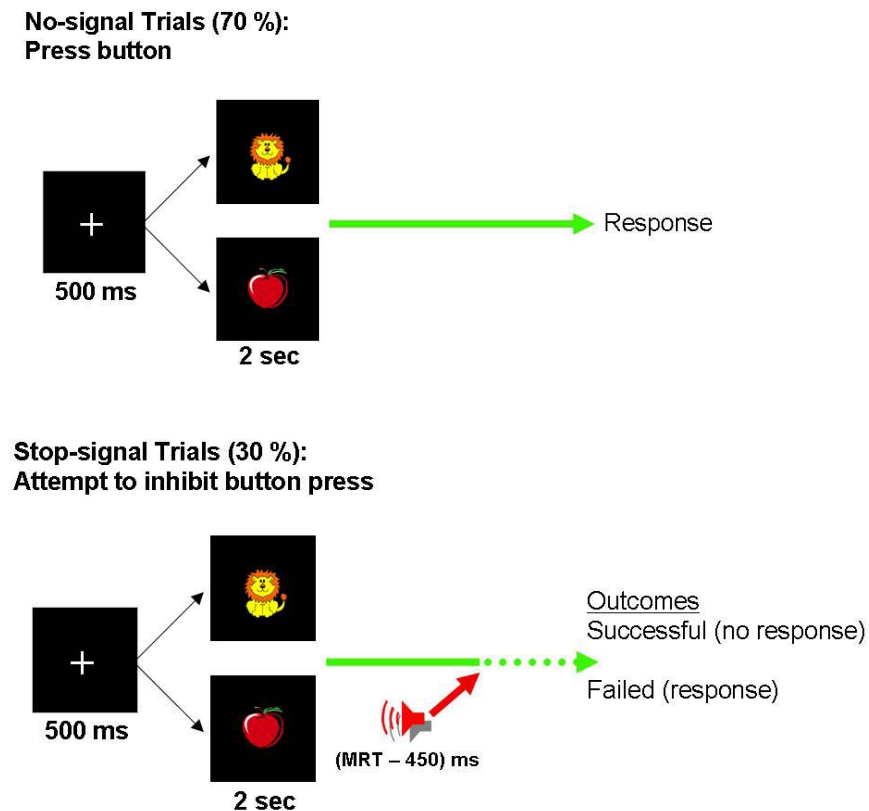
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<sup>19</sup> Subjects were instructed to respond to the binary choice-RT component of the stop-signal task with the index and middle fingers of the right hand so that the response side was the same between go/nogo and stop-signal tasks. This ensured a similar lateralisation of motor-related activity.

The stop-signal delay was varied relative to each subject's mean go reaction time (Go MRT) from the preceding block (Schachar & Logan, 1990b). The Go MRT was calculated using correct no-signal trials only, and was used to set the stop-signal delay to either (MRT – 0) ms, (MRT – 150) ms, (MRT – 300) ms, (MRT – 450) ms or (MRT – 600) ms. In the practice block, stop-signals were set to occur either 100, 200, 300, 400, or 500 ms after the onset of the go stimulus. Signal-signals could be presented either at or after go stimulus onset, but never before this point. If Go MRT was less than 600 ms, stop-signals for the (MRT – 600) ms delay were set to occur at the onset of the go stimulus.

The task included one practice block and three experimental blocks of 50 trials each. Subjects were told to respond quickly and accurately to the onset of visual go stimuli, and to withhold that response if they heard the stop-signal. Emphasis was placed on speed and accuracy for primary task performance, rather than successful inhibition. Subjects were told they should not wait for the tones as they would be unable to inhibit their response on every trial. It was explained that the onset of the stop-signal was dependent upon their RT to the primary task, such that delaying responses would only delay the presentation of the tones in subsequent blocks. Go MRT was displayed on the screen after each block, allowing subjects to rest briefly and to track their response speed, and also allowing the experimenter to monitor subjects for response-delaying strategies. In this instance, the experimenter emphasised the necessity for fast responding, and instructed the subject to try and obtain a shorter Go MRT in the next block.





**Figure 4.1.** A schematic of no-signal (upper panel) and stop-signal (lower panel) trials in the simple stop-signal task, and the successful or failed inhibitory outcomes

#### 4.3.5 Electrophysiological Recording

SCAN software version 4.2 (NeuroSoft Inc., 2001-2002) was used in conjunction with a Pentium III processor and 24 channels of Grass amplifiers for the acquisition and storage of electrophysiological data. The EEG was recorded from 17 sites (Fp1, Fp2, F3, F4, F7, F8, Fz, C3, C4, Cz, P3, P4, Pz, T3, T4, T5, T6) of the international 10-20 system, using an Electro-Cap referenced to linked ears and grounded mid-way between Fpz and Fz. Vertical eye movement (EOG) was measured with tin electrodes placed 1 cm above and below the left eye. Horizontal EOG was measured with tin electrodes placed 1 cm from the outer canthus of each eye. Impedance was kept below 5 k $\Omega$  for EOG electrodes and 3 k $\Omega$  for cap electrodes. EEG and EOG

signals were amplified 20 000 times, with a bandpass down 3 dB at 0.01 and 100 Hz, and were sampled through a 12-bit Labmaster A/D card at 512 Hz. Offline, EEG data were digitally filtered using a low-pass filter 3 dB down at 30 Hz. Vertical EOG was subtracted from the EEG using a regression algorithm in the time domain (Semlitsch, Anderer, Schuster, & Presslich, 1986). Horizontal EOG was manually inspected for gross eye movements and epochs were rejected if they contained activity greater than  $\pm 200 \mu\text{V}$ . All epochs were baseline corrected using the pre-stimulus period.

#### *4.3.6 Data Analysis*

##### **4.3.6.1 Performance measures**

Repeated measures ANOVAs were used to analyse all performance measures with Task (stop, nogo) as a within-subjects factor. Measures included Go MRT, inhibition probability, and the probability of committing an error of omission (i.e. no press) and choice (i.e. press lion when apple, and vice versa). Inhibition probability was corrected for the number of omission errors within a block (Tannock, Schachar, & Logan, 1995). An additional measure in the stop-signal task included mean SSRT. SSRT was estimated using the conventional method (see section 1.6.1 for details). Estimates of SSRT were calculated for each stop-signal delay with an inhibition probability of 10 – 90 % and then averaged across delays for each experimental block. Mean SSRTs were obtained by averaging SSRT across blocks to obtain separate mean SSRTs for each individual.

#### 4.3.6.2 Event-related Potentials

The ERP epoch was defined as 100 ms pre-stimulus to 900 ms post-stimulus onset. ERP averages were computed for go and nogo trials in the go/nogo task, and for stop-signals on successful and failed trials in the stop-signal task. Grand average waveforms were displayed for the purpose of defining each component. A large N1/P3 complex was observed in all ERP averages, and a smaller P2/N2 complex was observed in most averages. Peak amplitudes were quantified for N1 (80 to 190 ms), P2 (190 to 250 ms), N2 (200 to 300 ms), and P3 (260 to 450 ms) components as the maximum/minimum points within the prescribed latency ranges by means of an automatic peak-picking program, using Scan software (NeuroScan, v4.2), relative to the 100 ms pre-stimulus baseline period. Peak latencies for all components were fixed across all sites to the peak latency of the site of maximum amplitude (Picton et al., 2000; Spencer, Dien, & Donchin, 2001). Across tasks, the N1, P2 and P3 components were locked to Cz, while the N2 component was locked to Fz. Peak amplitudes were subsequently manually inspected.

Separate repeated-measures ANOVAs were used to examine ERP component amplitude at the midline sites (Fz, Cz, and Pz) in the go/nogo and stop-signal tasks separately, with “Trial” (1. go vs. nogo; 2. successful vs failed stop) and “Sagittal” as within-subject factors. Planned contrasts within the Sagittal factor compared Fz with Pz, and Cz with the mean of Fz and Pz. To examine differences between nogo and successful stop trials across the scalp, repeated-measures ANOVAs were used to analyse ERP component amplitudes at nine sites (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) as this allowed a topographic analysis in terms of a 3 x 3 (Laterality by Sagittal) matrix following Pfefferbaum, Ford, White and Roth (1989). Within-subject factors included: Laterality [Left (F3, C3, P3); Midline (Fz, Cz, Pz); Right (F4, C4, P4)] and Sagittal

[Frontal (F3, Fz, F4); Central (C3, Cz, C4); Parietal (P3, Pz, P4)] examining topography, and Task (nogo, successful stop). Planned contrasts within the Sagittal factor compared the frontal and parietal regions, and the mean of these with the central region, while contrasts within the Laterality factor compared the left and right hemispheres, and the mean of these *lateral* regions with the midline. These planned contrasts provide optimal information on the topographic distribution of the amplitude of each component quantified at the peak latency of the site of maximum amplitude. Analyses for component peak latency excluded site contrasts.

As all contrasts were planned and there were no more of them than the degrees of freedom for effect, no Bonferroni-type adjustment to alpha was necessary (Tabachnick & Fidell, 1989). Also, the single degree of freedom contrasts are not affected by violations of symmetry assumptions common in repeated measures analyses, and thus do not require Greenhouse-Geisser type corrections. In order to interpret scalp distributions within Trials and Tasks, the data were normalised with the vector scaling method, using the square root of the average of squared across-subjects mean amplitude (McCarthy & Wood, 1985), and only topographic interactions that remained significant after normalisation are reported. Unless otherwise indicated, degrees of freedom for all statistical effects reported are (1, 34).

## 4.4 Results

### 4.4.1 Performance Measures

Table 4.1 outlines the means and standard deviations for performance measures. In the stop-signal task, Go MRT was longer ( $F = 7.8, p < .05$ ), there was a greater proportion of omission errors ( $F = 5.2, p < .05$ ) and inhibition probability was reduced

( $F = 35.7$ ,  $p < .001$ ), relative to the go/nogo task. However, there was no difference in the proportion of choice errors to go stimuli ( $F < 1$ ). SSRT was estimated to be 226.4 ms (SD = 73.2 ms).

**Table 4.1. Means and standard deviations for performance measures in the go/nogo and stop-signal tasks.**

	Go MRT	Omission Errors	Choice Errors	P(Inhibition)
<b>Go/nogo task</b>	423.7 (54.3)	1.8 (1.1)	1.4 (1.7)	97.9 (2.8)
<b>Stop-signal task</b>	553.2 (128.9)	3.4 (2.2)	1.7 (1.6)	55.7 (10.8)

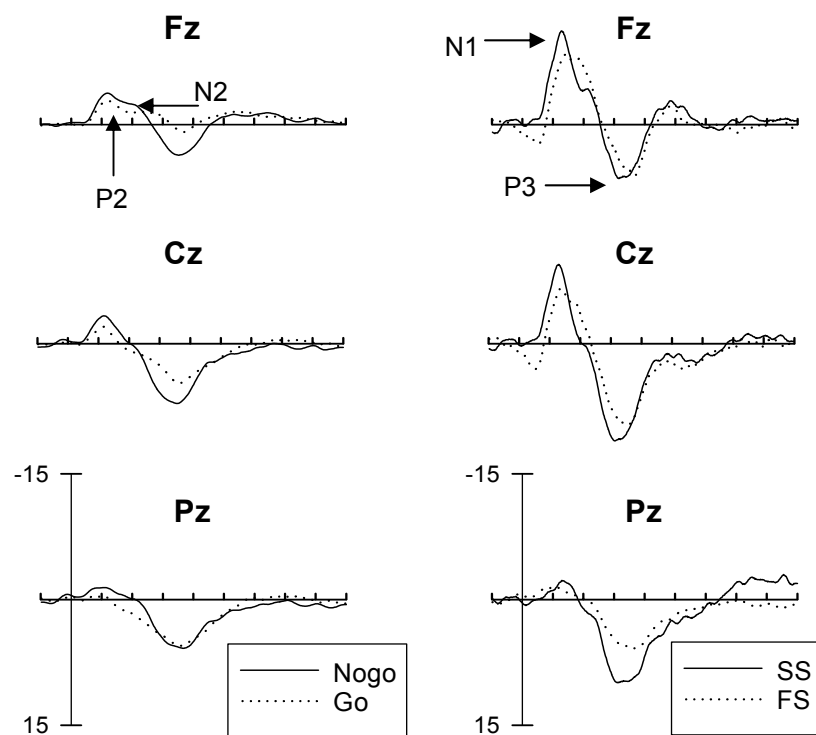
**Notes and Abbreviations:** (1) Mean within-subject standard deviations shown in brackets, (2) Reaction time in milliseconds, (3) Errors and P(Inhibition) in percentages; (3) Go MRT = Mean reaction time to go stimuli (restricted to no-signal trials in the stop-signal task); P(Inhibition) = Inhibition probability.

#### 4.4.2 Event-related Potentials

Throughout this thesis, statistical effects related to ERP components are described, *within the contrasts performed*, in terms of the region(s) in which components showed their maximum amplitude. For example, a component may show right-midline, fronto-central maximas. This means that, within the Laterality factor, the component was larger in the *midline* compared to the mean of the left and right hemispheres (termed lateral regions), and in the *right* compared to the left hemisphere, resulting in a right-midline maximum. Within the Sagittal factor, the component was larger in the *frontal* compared to parietal region, and in the *central* compared to the mean of the frontal and parietal regions, resulting in a fronto-central maximum. Frontal/parietal and lateral region maximas indicate that a component was larger in the mean of the frontal and parietal regions compared to the central region, and in the mean of the left and right regions compared to the midline region. This form of reporting provides a concise description of the relative spread of activation across the scalp for each component at the peak latency of the site of maximum amplitude.

#### 4.4.2.1 Cued Go/Nogo Task

Figure 4.2 (left panel) depicts the grand average ERP waveforms for go and nogo trials at the midline sites. An inspection of the waveforms for go trials revealed an N1 component (117.1 ms) with a fronto-central distribution, a small P2 (202.8 ms) and N2 (248.3 ms) at the frontal site, and a large P3 (368.5 ms) with a parietal maximum. Nogo trials showed a fronto-central N1 (120.3 ms), frontal P2 (203.0 ms), frontal N2 (240.3 ms), and a fronto-central P3 (360.1 ms).



**Figure 4.2.** Grand average ERP waveforms at the midline sites for nogo versus go trials (left panel) and for successful stop (SS) versus failed stop (FS) trials (right panel). Notes: for this and the subsequent figure, (1) y-axis (shown at Pz) =  $\pm 15$   $\mu\text{V}$ , (3) vertical bar indicates stimulus onset, (4) x-axis ticks = 100 ms, (5) negative-going amplitude is up.

Table 4.2 summarises the following effects and provides means. Larger amplitude was found for nogo compared to go trials for the N1 ( $F = 18.1, p < .001$ ), N2 ( $F = 5.4, p < .05$ ) and P3 components ( $F = 4.9, p < .05$ ) (see Figure 4.1). P2 amplitude showed a parietal > frontal effect for go trials that was reduced for nogo trials ( $F = 5.8, p < .05$ ). N2 amplitude for go trials showed a frontal > parietal effect that was reduced for nogo trials, mainly due to greater activity in the parietal region for nogo trials ( $F = 28.7, p < .001$ ). P3 amplitude for nogo trials showed a frontal maximum; go trials showed a parietal maximum ( $F = 18.1, p < .001$ ). Although a central > frontal/parietal effect was found for nogo trials ( $F = 7.2, p < .05$ ), this effect did not remain after normalisation ( $F = 1.4, p = .364$ ). There were no main effects involving peak latency.

**Table 4.2. A summary of ERP component amplitude analyses and means for go and nogo trials. Notes: for this and subsequent tables in this thesis, (1) the “Effect” column indicates the significant main effects of the factors examined and the significant interactions between these factors, (2) the “Contrast” column indicates which of the planned contrasts within each of the significant main effects and interactions were significant (3) the “Effect Details” column indicates the means for each effect, (4) all means values are in  $\mu V$ .**

	Effect	Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>N1</b>	Trial	Nogo vs. Go	-2.6 vs. -1.3	18.1	.000
<b>P2</b>	Trial x Sag	Fz vs. Pz	Nogo: 1.5 vs. 1.4; Go: 1.4 vs. 2.3	5.8	.021
<b>N2</b>	Trial	Nogo vs. Go	-0.4 vs. 0.7	5.4	.026
	Trial x Sag	Fz vs. Pz	Nogo: -0.6 vs. -0.4; Go: -0.6 vs. 1.6	28.7	.000
<b>P3</b>	Trial	Nogo vs. Go	5.4 vs. 4.2	4.9	.033
	Trial x Sag	Fz vs. Pz	Nogo: 7.2 vs. 5.9; Go: 4.3 vs. 5.0	18.1	.000
		Cz vs. Fz/Pz	Nogo: 3.1 vs. 6.7; Go: 3.2 vs. 4.7	7.2	.011

#### 4.4.2.2 Simple Stop-signal Task

Figure 4.2 (right panel) depicts the grand average ERP waveforms for successful and failed stop trials. This figure shows that successful stop trials were associated with a prominent N1 component in the fronto-central region (135.6 ms), a barely visible P2

(203.0 ms) and N2 (218.3 ms) in the frontal region on the descending flank of the N1, and a large P3 (338.9 ms) in the centro-parietal region. In contrast, failed stop trials were associated with a large, bi-phasic negative component, particularly in the fronto-central region, which was distinguished as containing the partially overlapped N1 (153.6 ms) and N2 (217.6 ms) components. Although P2 (202.7 ms) was not evident in the grand averages, it appeared in most individual ERP averages and showed a central maximum, while the P3 component (351.4 ms) was also largest in this region.

Table 4.3 summarises the following effects and provides means. A main effect was found for N2 only, with larger amplitude across the scalp for failed compared to successful stop trials ( $F = 4.7$ ,  $p < .05$ ; see Figure 4.1, right panel). N1 amplitude for successful stop trials showed a fronto-central maximum that was reduced for failed stop trials ( $F = 7.4$ ,  $p = .01$ ). P2 showed no significant effects. However, P3 showed a parietal maximum for successful stops, while amplitude for failed stop trials was equipotential across this region ( $F = 4.9$ ,  $p < .05$ ). With respect to latency, N1 peaked later for failed compared to successful stop trials ( $F = 12.8$ ,  $p = .001$ ; see Table 4.4).

**Table 4.3. A summary of ERP component amplitude analyses and means for successful and failed stop trials.**

	Effect	Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>N1</b>	Trial x Sag	Fz vs. Pz	SS: -14.0 vs. -4.2; FS: -7.9 vs. -5.0	7.4	.010
		Cz vs. Fz/Pz	SS: -12.3 vs. -9.1; FS: -5.3 vs. -10.7	12.6	.001
<b>P2</b>	No effects				
<b>N2</b>	Trial	SS vs. FS	-3.3 vs. -5.9	4.7	.037
<b>P3</b>	Trial x Sag	Fz vs. Pz	SS: 10.3 vs. 13.6; FS: 10.0 vs. 10.9	4.9	.033

**Abbreviations:** SS = Successful stop trial; FF = Failed stop trial.



**Table 4.4. A summary of peak latency analyses and means for all trial comparisons. Notes: Mean peak latencies in the “Effect Details” column are in ms.**

	Effect	Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>N1</b>	Trial	SS vs. FS	134.0 vs. 147.0	12.8	.001
	Trial	SS vs. Nogo	134.0 vs. 147.0	4.9	.033
<b>P2</b>	No effects				
<b>N2</b>	Trial	SS vs. Nogo	214.4 vs. 225.0	5.8	.022
<b>P3</b>	Trial	SS vs. Nogo	339.6 vs. 353.0	7.4	.010

#### 4.4.2.3 Nogo versus Successful Stop Trials

Figure 4.3 depicts the grand average ERP waveforms for successful stop and nogo trials at nine sites (left panel) and the topographic distribution maps of the amplitude of each component for successful stop and nogo trials (right panel). The maps were generated using Significance Probability Albert Mapping (SPAM) software (Haig, 1993), which were derived from the component’s mean amplitude at the 17 electrode sites, providing a representation of the relative regional activation of the amplitude of each ERP component at the peak latency of the site of maximum amplitude.

Table 4.5 summarises the following effects and provides means. Main effects were found for N1 ( $F = 94.7, p < .001$ ), P2 ( $F = 7.5, p = .01$ ), N2 ( $F = 5.9, p < .05$ ) and P3 ( $F = 46.8, p < .001$ ), where amplitude was larger for successful stop compared to nogo trials.

N1 showed a fronto-central maximum for successful stop trials and a frontal maximum for nogo trials ( $f^{20}$  vs.  $p$ ,  $F = 32.5, p < .001$ ;  $c$  vs.  $f/p$ ,  $F = 69.0, p < .001$ ). Furthermore, nogo trials showed a parietally-maximal midline > lateral effect,<sup>21</sup> while

<sup>20</sup> See notes for Table 4.5 for description of abbreviations.

<sup>21</sup> The format of the term used to describe this statistical effect will be used throughout this thesis when Lateral x Sagittal interactions are concerned. For example, a *frontally-maximal midline > lateral* region

amplitude was equipotential in the parietal region for successful stop trials ( $F = 14.3, p < .01$ ). Finally, a centrally-maximal left > right effect occurred for nogo trials, while successful stops showed a midline maximum in this region (cL to cR vs. f/pL to f/pR,  $F = 10.4, p < .01$ ; cM to cL/R vs. f/pM to f/pL/R,  $F = 43.0, p < .001$ ; see Figure 4.2, right panel).

Successful stop P2 was larger in the right than left hemisphere; nogo P2 showed the converse effect ( $F = 6.9, p < .05$ ). Furthermore, P2 showed a midline > lateral effect that was maximal in the central region for successful stop trials ( $F = 31.3, p < .001$ ), and minimal in this region for nogo trials ( $F = 7.2, p < .05$ ).

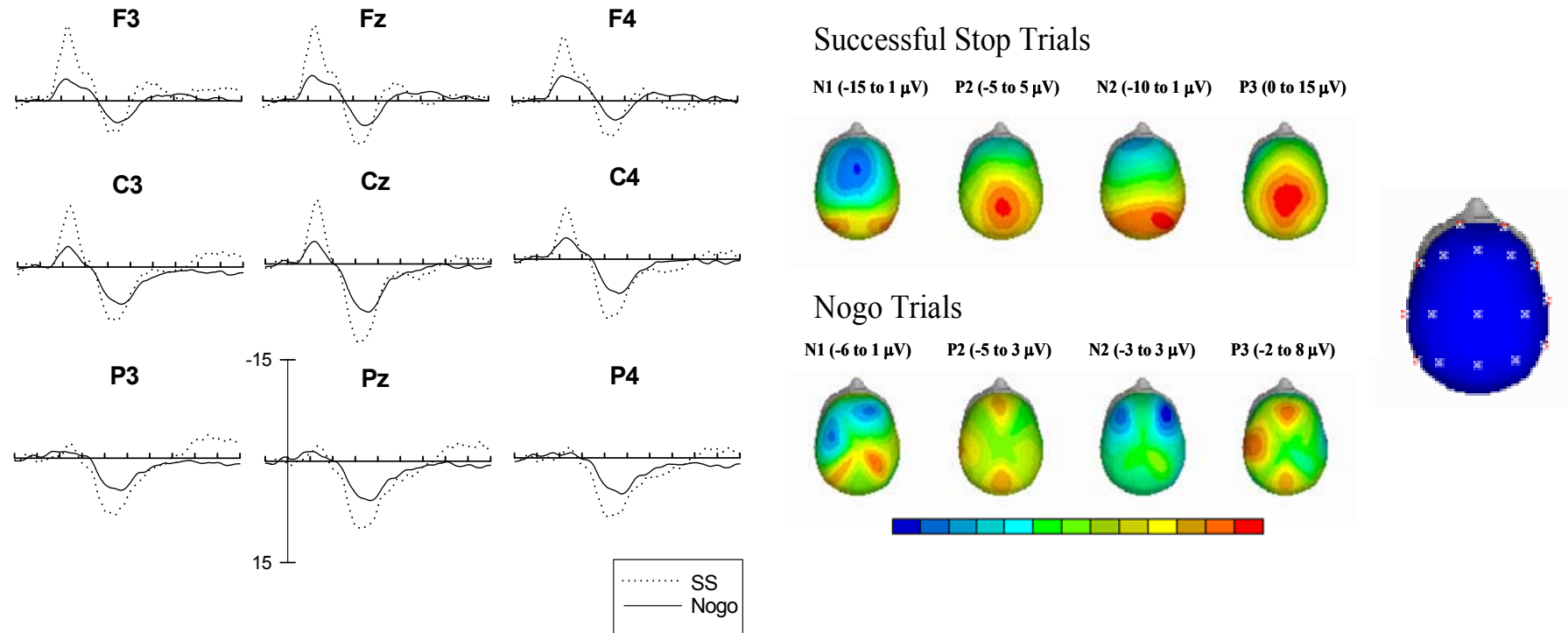
N2 amplitude showed a frontal > parietal effect that was larger for successful stop compared to nogo trials ( $F = 19.5, p < .001$ ). Furthermore, a left > right was maximal in the frontal region for successful stops, while nogo trials showed a right > left effect in the frontal region ( $F = 6.1, p = .001$ ).

P3 amplitude showed a centro-parietal maximum for successful stop trials and a frontal maximum for nogo trials (f vs. p,  $F = 19.4, p < .001$ ; c vs. f/p,  $F = 28.8, p < .001$ ). Furthermore, a left > right effect occurred for nogo trials ( $F = 15.1, p < .001$ ), and a midline > lateral effect for successful stop trials ( $F = 8.0, p < .01$ ), with both these laterality effects maximal in the central region (cL to cR vs. f/pL to f/pR,  $F = 9.4, p < .01$ ; cM to cL/R vs. f/pM to f/pL/R,  $F = 48.5, p < .001$ ).

With respect to latency, N1 ( $F = 4.9, p < .05$ ), N2 ( $F = 5.8, p < .05$ ) and P3 ( $F = 7.5, p < .05$ ) peaked later for nogo compared to successful stop trials (see Table 4.4).

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effect indicates that the component is larger in the midline than the lateral regions, but that this effect differs along the Sagittal dimension, being larger in the parietal than frontal region.



**Figure 4.3.** The left panel depicts the grand average ERP waveforms across the nine sites for successful stop versus nogo trials. The right panel depicts the topographic distribution of the amplitude of each ERP component for successful stop trials (top) and nogo trials (bottom). Note: for this and all subsequent topographic maps, the range indicated shows the smallest and largest values that correspond to the blue and red extreme points of the colour spectrum scale (shown at the bottom of the figure) respectively. Therefore, “hot” colours indicate large values (positive-going) and “cool” colours indicate small values (negative-going). All 17 electrode sites were used to generate the maps (electrodes sites shown on the example blue head map at the right of the figure).

**Table 4.5. A summary of ERP component amplitude analyses and means for nogo and successful stop trials.**

	Effect	Contrast	Effect Details	F	p
<b>N1</b>	Trial	Nogo vs. SS	-2.5 vs. -9.5	94.7	.000
	T x Sag	f vs. p	SS: -13.4 vs. -4.0 Nogo: 3.3 vs. 0.1	32.5	.000
		c vs. f/p	SS: -11.1 vs. -8.7 Nogo: -1.3 vs. -1.6	69.0	.000
	T x Sag x Lat	fM to fL/R vs. pM to pL/R	SS: -13.9 to -13.2 vs. -4.2 to -3.9 Nogo: -4.4 to -4.5 vs. -2.0 to -0.3	14.3	.001
		cL to cR vs. f/pL to f/pR	SS: -11.3 to -9.7 vs. -9.0 to -8.0 Nogo: -4.5 to -1.5 vs. -2.4 to -2.5	10.4	.003
		cM to cL/R vs. f/pM to f/pL/R	SS: -12.3 to -10.5 vs. -9.1 to -8.5 Nogo: -1.3 to -3.0 vs. -3.2 to -2.4	43.0	.000
<b>P2</b>	Trial	Nogo vs. SS	0.4 vs. 2.8	7.5	.010
	T x Lat	L vs. R	SS: 2.1 vs. 3.0 Nogo: 0.4 vs. -0.2	6.9	.013
	T x Sag x Lat	fM to fL/R vs. pM to pL/R	SS: 0.8 to 0.6 vs. 4.7 to 4.2 Nogo: 1.5 to -0.5 vs. 1.4 to 0.4	7.2	.011
		cM to cL/R vs. f/pM to f/pL/R	SS: 4.3 to 2.8 vs. 2.7 to 2.4 Nogo: -0.3 to 0.4 vs. 1.5 to -0.1	31.3	.000
<b>N2</b>	Trial	Nogo vs. SS	-0.9 vs. -3.3	5.9	.020
	T x Sag	f vs. p	SS: -6.3 vs. -0.7 Nogo: -1.9 vs. -0.3	19.5	.000
	T x Sag x Lat	fL to fR vs. pL to pR	SS: -6.7 to -6.0 vs. -1.0 to -0.5 Nogo: -2.2 to -2.7 vs. -0.7 to 0.1	6.1	.001
<b>P3</b>	Trial	Nogo vs. SS	4.7 vs. 11.5	46.8	.000
	T x Sag	f vs. p	SS: 9.2 vs. 12.3 Nogo: 2.8 vs. 3.6	19.4	.000
		c vs. f/p	SS: 12.9 vs. 11.1 Nogo: 3.4 vs. 3.2	28.8	.000
	T x Lat	L vs. R	SS: 10.2 vs. 11.1 Nogo: 5.1 vs. 3.5	15.1	.000
		M vs. L/R	SS: 13.0 vs. 10.7 Nogo: 5.4 vs. 4.3	8.0	.008
	T x Sag x Lat	cL to cR vs. f/pL to f/pR	SS: 11.2 to 12.2 vs. 9.7 to 10.6 Nogo: 6.6 to 3.2 vs. 4.3 to 3.7	9.4	.004
		cM to cL/R vs. f/pM to f/pL/R	SS: 15.1 to 11.7 vs. 11.9 to 10.1 Nogo: 3.1 to 4.9 vs. 6.6 to 4.0	48.5	.000

**Abbreviations:** vs. = versus; SS = Successful stop trial; FS = Failed stop trials; Sagittal (Sag): f = frontal (mean activity at F3, Fz and F4; previously defined in Section 4.4.2.3); c = central (mean activity at C3, Cz and C4); p = parietal (mean activity at P3, Pz and P4); f/p = frontal/parietal (mean activity of F3, Fz, F4, P3, Pz and P4); Laterality (Lat): L = left (mean of activity at F3, C3 and P3); R = right (mean of activity at F4, C4 and P4); M = midline (mean of activity at Fz, Cz and Pz); L/R = left/right (lateral regions; mean of activity at F3, F4, C3, C4, P3 and P4); Laterality by Sagittal interactions: fL = F3; fR = F4; fM = Fz; fL/R = mean of activity at F3 and F4; cL = C3; cR = C4; cM = Cz; cL/R = mean of activity at C3 and C4; pL = P3; pR = P4; pM = Pz; pL/R = mean of activity at P3 and P4; f/pL = mean of F3 and P3; f/pR = mean of activity at F4 and P4; f/pM = mean of activity at Fz and Pz; f/pL/R = mean of activity at F3, F4, P3 and P4.

## 4.5 Discussion

Although interpretations of the functional significance of ERPs for nogo trials in go/nogo tasks have been used to explain inhibitory effects in the stop-signal task, brain imaging studies have shown dissimilar regions of activation during the inhibition of responses in the two tasks (Rubia et al., 2001), and during the inhibition of different types of responses in general (Dias et al., 1997; Mostofsky et al., 2003). In the present study, nogo ERPs in a cued go/nogo task were compared to successful stop ERPs in a simple stop-signal task in a group of young adults using auditory stimuli. However, firstly, go trials were compared to nogo trials from the go/nogo task, and successful stop trials with failed stop trials from the stop-signal task, to clarify the functional role of each component.

### 4.5.1 Cued Go/Nogo Task

In the go/nogo task, larger amplitudes were found for the rare nogo trial, relative to the frequent go trial, for the N1, N2 and P3 components. Larger N2 and P3 amplitudes for nogo trials are consistent with a large body of literature that has associated these components on nogo trials with response inhibition (Eimer, 1993; Kok, 1986). When nogo stimuli occur less frequently than go stimuli, as in the present study, the difference in N2 amplitude between nogo and go trials is observed profusely across the scalp (Eimer, 1993). This difference in topographic distribution has led to suggestions that N2 may reflect two components: one affected by stimulus probability with diffuse activation across the scalp, and the other affected by the differential go or nogo response assignment and localised to the frontal region (Eimer, 1993; Nieuwenhuis et al., 2003). In the present study, enhanced N2 amplitude across the

midline sites for rare nogo compared to frequent go trials was largest in the parietal region. Therefore, it is likely that the N2 main effect of trial may have reflected the difference in the proportion of go and nogo trials, as well as inhibitory requirements.

Nogo P3 typically has a frontal or fronto-central distribution at equal stimulus probabilities, and a more central distribution with a decrease in stimulus probability, while go P3 has a parietal or centro-parietal distribution that does not appear to vary with stimulus probability (Pfefferbaum & Ford, 1988; Squires et al., 1977; Squires et al., 1975). In line with previous findings, go P3 had a parietal distribution while nogo P3 had a frontal maximum, supporting this component's relation to a frontal inhibitory system (Falkenstein et al., 2002; Pfefferbaum & Ford, 1988). Therefore, nogo P3 may have predominantly reflected inhibitory requirements. However, P3 amplitude varies with stimulus probability, regardless of the task assigned to the stimulus, therefore, this factor cannot be ruled out completely (Banquet, 1981; Bruin & Wijers, 2002; Czigler et al., 1996; Duncan-Johnson & Donchin, 1977).

#### 4.5.2 *Simple Stop-signal Task*

Typical effects in the stop-signal task include larger amplitude for successful stop compared to failed stop trials for the N1 (Bekker et al., 2005a), the converse effect for N2 (Dimoska et al., 2003; van Boxtel et al., 2001), while the P3 has shown both effects. For example, de Jong et al. (1990) found enhanced P3 amplitude for successful compared to failed stop trials, while Kok et al. (2004) found the converse effect. In the present study, N1 for successful stop trials showed a fronto-central maximum, with this effect reduced for failed stop trials. At the N1 latency range, a number of individual components have been reported previously (Näätänen & Picton, 1987). While the exogenous N1 component is maximal at the vertex (Näätänen & Picton, 1987), the

fronto-central distribution of the difference between successful and failed stop trials corresponds to the processing negativity (PN), an early, broad negative component that overlaps the exogenous N1 and is sensitive to attention (Hillyard et al., 1973; Näätänen, Gaillard, & Mäntysalo, 1978). Reduced amplitude may reflect the exclusion of sensory input from further processing or a reduced attentional effect (Hillyard et al., 1973). Therefore, an enhanced fronto-central N1 on successful stop trials may be associated with a greater attentional switch, which results in more effective sensory processing of stop-signals.

Although there were no significant effects found for the P2 component, the N2 showed a main effect with larger amplitude for failed compared to successful stop trials across the midline. Enhanced N2 amplitude for failed compared to successful trials has previously been interpreted as either reflecting greater inhibitory activation on trials where inhibition is more difficult (van Boxtel et al., 2001), or a signal that detects a response on a stop-signal trial and feeds back this information to higher-order, executive control centres (Kok et al., 2004). An alternative interpretation offered by the go/nogo literature is that the N2 reflects an evaluative mechanism in the ACC that detects conflict between concurrently activated responses (Nieuwenhuis et al., 2003), with enhanced amplitude for failed stop trials reflecting the detection of a high degree of conflict between the correct go response and the failed inhibitory response. Therefore, the functional significance of the stop N2 in adults is, at present, unclear. This issue is addressed in a later study of this thesis (see Chapter 6).

The typical enhancement of P3 amplitude on successful compared to failed stop trials has previously been interpreted as reflecting greater inhibitory activation on successful stop trials (de Jong et al., 1990; Dimoska et al., 2003). However, in the present study, the effect was largest in the parietal region due to enhanced amplitude for

successful stop trials in this region. As a parietal enhancement does not correspond to either a frontal (Kok, 1986; Pliszka et al., 2000) or a central (Kok et al., 2004; Ramautar et al., 2004) inhibitory source, it is unlikely that the enhanced amplitude for successful compared to failed trials reflects inhibitory requirements. Nonetheless, this does not discount the P3's relation to inhibition. Although Kok et al. (2004) found larger amplitude for failed compared to successful stop trials, the successful stop P3 was interpreted as reflecting an inhibition process in the pre or primary motor cortex, as shown through dipole source modelling. Therefore, P3 does not necessarily have to be larger on successful than failed stop trials to reflect inhibitory processing.

#### 4.5.3 *Nogo versus Stop-signal Inhibition*

As anticipated, performance was generally poorer in the stop-signal compared to go/nogo task. Responding to go stimuli was significantly faster and more accurate, while inhibition probability was greater in the go/nogo than stop-signal task. The latter finding supports the notion that subjects found it considerably more difficult to inhibit an *ongoing* response in the stop-signal task, relative to a *prepared* response in the go/nogo task, despite slower responses usually being easier to inhibit (Logan, 1994). This is, of course, due to the nature of the tasks. While inhibition can be evoked during response preparation in the go/nogo task, inhibition in the stop-signal task is evoked at variable stages of response processing.

ERP findings showed that although stop-signals and nogo stimuli occurred with equal probability, stop-signals were associated with generally larger component amplitudes and shorter peak latencies. These effects were probably the result of the context within which stimuli were presented. Firstly, enhanced N1 and P2 amplitudes in the stop-signal task may have reflected a greater impingement on the auditory cortex



because of the switch from silence to auditory stimulation, as opposed to the switch from the frequency of one auditory stimulus to another in the go/nogo task (Näätänen & Picton, 1987; Oades, 1998). Furthermore, longer peak latencies for all components on nogo compared to successful stop trials may have reflected the fact that the mere detection of an auditory stimulus in the stop-signal task allowed faster activation of inhibitory processing than the requirement to discriminate between go and nogo stimuli in the go/nogo task (van Boxtel et al., 2001). Therefore, the single stop-signal in the stop-signal task was associated with greater and earlier sensory processing than the nogo stimulus in the go/nogo task, which was presented relative to the go stimulus.

Although van Boxtel et al. (2001) found no difference in the topographic distribution of N2 amplitude across the lateral-frontal region between nogo and stop-signals, the present findings showed larger amplitude in the left than right hemisphere for successful stop trials and the converse for nogo trials. Furthermore, across the sagittal region, a frontal > parietal gradient for successful stop N2 was reduced for nogo N2. Therefore, the topographic distribution of N2 differed between the stop-signal and go/nogo tasks. This study, however, differs from van Boxtel et al. (2001) in a number of respects. Firstly, they included nogo stimuli and stop-signals within the same task, while the present study compared them between tasks. Secondly, they used visual stimuli, which are known to produce a larger, and potentially different N2 than that to auditory stimuli (Falkenstein et al., 1995b). Lastly, they quantified nogo N2 at a much later latency than that in the present study. An inspection of Figure 5 in van Boxtel et al. (2001, p. 252) revealed a small negative component for nogo trials at a similar latency to the stop N2 that was not reported, but was nonetheless reduced for nogo compared to stop-signal trials. This nogo N2 may be similar to the component quantified in the present study.

In line with previous findings and with the notion of a frontal inhibition system (Bokura, 2001; Casey et al., 1997; Durston et al., 2002; Garavan et al., 1999; Kiefer et al., 1998; Konishi et al., 1999), nogo P3 showed a frontal maximum. In contrast, successful stop P3 showed a centro-parietal maximum, with the largest difference between successful stop and nogo trials occurring in the centro-parietal region. This corresponded to dipole source modelling, which suggests a central source for stop-signal inhibition near or in the motor or premotor cortex (Kok et al., 2004; Ramautar et al., 2004). These findings suggest differential inhibitory processing between tasks, however, this does not necessarily imply different *agents* of inhibition at work. One of the key differences between the go/nogo and stop-signal tasks is that responses may be stopped at different stages of processing (see sections 1.9 and 3.6.1). It is likely that the frontal maximum for nogo P3 may reflect response selection (Rubia et al., 2001) or modulation at early preparational stages of processing. In contrast, as responses in the stop-signal task are typically stopped at more progressed stages of processing, the centro-parietal maximum of the successful stop P3 may reflect the manifestation of inhibitory control in or near the motor or premotor cortex (Kok et al., 2004), believed to be the last cortical site of inhibition (Band & van Boxtel, 1999; Brunia, 1993; Brunia, 2003). Therefore, the different topographic distribution of P3 for nogo and successful stop trials may reflect inhibition acting on different stages of response processing, rather than distinct agents of inhibition at work (Band & van Boxtel, 1999).

Using fMRI, Rubia et al. (2001) found a left versus right hemispheric dissociation for nogo and stop-signal inhibition, respectively. However, in the present study, using ERPs, successful stop P3 was not lateralised to the right hemisphere. Although successful stop P2 showed a right lateralisation, this component has previously been associated with sensory, rather than motor, inhibition (Hegerl,

Karnauchow, Herrmann, & Mueller-Oerlinghausen, 1992; Oades, 1998). Therefore, stop-signal inhibition did not show a lateralisation to the right hemisphere. In contrast, in line with Rubia et al. (2001) and a number of ERP studies (Bokura, 2001; Kiefer et al., 1998; Kok, 1986; Roberts et al., 1994), nogo trials showed a left lateralisation for P3, as well as P2 across the sagittal region, and N1 in the central region. Therefore, nogo inhibition appeared to be associated with a left-hemispheric frontal process that may be related to response selection (Rubia et al., 2001). However, it should be noted that while the spatial resolution of fMRI is superior to the examination of the topographic distribution of ERPs, activity reflects an average across a lengthy period. In contrast, ERPs provide a temporal dissociation between individual stages of processing. Thus, brain imaging and ERP component distribution are not likely to reflect the same processes.

An examination of stop-signal task performance in Rubia et al. (2001) shows unusually long Go RTs, and a high inhibition probability. These behavioural findings suggest that inhibition in their stop-signal tasks may not have been performed with the urgent inhibitory action that is typically required in this task. Rather, execution of a response may have been delayed until subjects knew that a stop-signal would not occur. This strategy may evoke a different inhibition process (Dias et al., 1997). In contrast, go/nogo task performance in Rubia et al. (2001) was typical. However, although a hemispheric dissociation for nogo and stop-signal inhibition was only partly supported, these findings show that nogo and stop-signal inhibition evoke distinct inhibitory processing.

#### 4.5.4 *Limitations*

A limitation of this study was the use of a different tone pitch for nogo stimuli and stop-signals. Pitch has been shown to typically affect very early brain stem auditory-evoked potentials, but it is possible that this may have also contributed partly to the early N1 differences between stimuli (Näätänen & Picton, 1987). Later components would not have been affected. Nevertheless, this is not a major limitation as numerous go/nogo or attend/non-attend studies compare tones of varying pitch and do not consider pitch to be an influential factor for endogenous components (i.e. N1 and later). An issue identified in this study was the difficulty in picking P2 and N2 components for stop-signal ERPs because of their small magnitude and inconsistent appearance between trial-types and subjects. As P2 and N2 effects may have overlapped considerably, the following studies in this thesis use mean amplitude in this latency range.

#### 4.5.5 *Summary*

In summary, performance findings showed that the inhibition of an ongoing response in the stop-signal task was a considerably more difficult task than the inhibition of a prepared response in the cued go/nogo task. An examination of ERPs for successful stop trials revealed larger amplitudes and shorter peak latencies for all components, relative to nogo trials, suggesting faster and greater activation of inhibitory processes in response to the stop-signal. However, the key finding revealed the manifestation of distinct inhibitory processing, as reflected in the P3, for nogo and stop-signal trials. Nogo trials were associated with a predominantly left-hemispheric frontal network, which was interpreted as reflecting inhibition at early stages of response

preparation, that is, when the go or nogo response was being selected. In contrast, successful stop P3 was maximal in the centro-parietal region, did not show a lateralisation, and was interpreted as reflecting inhibition acting on response processing near or in the motor or premotor cortex. The findings presented here suggest that successful stop and nogo ERPs reflect the manifestation of inhibition at differential sites of response processing. Therefore, interpretations for nogo ERPs should not be automatically applied to the explanation of stop-signal ERPs.

An issue which is currently under debate is whether the inclusion of an additional stimulus discrimination to the stop-signal response results in the activation of a slower, and potentially, different inhibition process (De Jong et al., 1995; Bedard et al., 2002; van den Wildenburg et al., 2004). Therefore, the next study varies the stopping component of the stop-signal task so that it will be analogous to the go/nogo task, with subjects having to make a stop/no-stop discrimination. This allows an insight into inhibitory processing and strategies when stimulus discrimination is included as an additional process to the stop-signal response.

## **5. Study II - Effects of stimulus discrimination in the response to stop-signals: Simple versus selective inhibition\***

### **5.1 Abstract**

The aim of the present study was to examine whether the inclusion of a stimulus discrimination in the response to the auditory stop-signal would increase the latency of this response and whether simple and selective stopping would be associated with activation of different cortical inhibition processes. Adult participants performed simple and selective versions of the stop-signal task, consisting of a visual choice RT task and a 1500 Hz tone presented on 30 % of trials instructing subjects to inhibit their response. In the selective condition, a task-irrelevant 1000 Hz tone occurred on a different 30 % of trials. The discrimination required between stop- and ignore-signals in the selective condition did not affect SSRT, but reduced the proportion of successful inhibitions, due to greater within-subject variability in responding. ERPs had similar peak latencies between conditions, supporting the notion that the additional discrimination component, as reflected in the broadly distributed N2 activity, occurred in parallel with inhibitory processes. The distribution of the P3 component was similar between conditions, suggesting activation of similar inhibition processes. These findings suggest that subjects activated a fast, non-selective, inhibition process to stop responses in both simple and selective conditions.

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\* Dimoska, A., Johnstone, S.J., Barry, R.J. (submitted). The effect of stimulus discrimination in response to stop-signals: Simple versus selective inhibition. *International Journal of Psychophysiology*.

## 5.2 Introduction

Researchers using the stop-signal task to examine inhibition have primarily focussed on evoking a simple inhibitory response via a single stop-signal. In the typical (or simple) stop-signal task, the auditory stop-signal always instructs the subject to inhibit the *go response*. In real-life situations, however, rarely do we stop an action or thought without going through a process of discrimination between alternative choices. Should I stop? Or is it permissible to execute the current action? An example of such a process might occur whilst driving. For example, when driving a motor vehicle (a primary task) traffic lights present three possible options which will modify your motor output (go, stop, or prepare to stop). Few laboratory studies have examined the nature of inhibitory processing when such a stimulus discrimination or choice is included in the response to the stop-signal.

The selective stop-signal task allows the measurement of a more complicated form of stopping which involves subjects having to discriminate between one of two possible stop-signals, and only inhibiting responses to one tone (the stop-signal), but not the other (termed the ignore-signal) (Riegler, 1986 as cited in Logan, 1994). As outlined in section 1.7.2, complicating the stop-signal inhibitory response in this manner has been found to result in slower SSRTs. This has led researchers to suggest a slow, local mode of stopping for selective inhibition, as opposed to a fast, global model for simple inhibition (Logan, 1994; van den Wildenberg & van der Molen, 2004b). However, a longer SSRT in a selective stop-signal task may merely reflect an increase in the duration of perceptual processing, rather than the activation of a distinct inhibition process (Band & van Boxtel, 1999). The notion of a slow, local mode of inhibition may be better applied to the stop-change task, where slower inhibitory

processing reflects the re-organisation of response processes (Band & van Boxtel, 1999; Logan & Cowan, 1984).

Using the LRP, De Jong et al. (1995) attempted to determine whether simple and selective inhibition may involve the same inhibition mechanism. They found supra-threshold LRP activity on some successful stop trials in both simple and selective stop-signal tasks and interpreted this to mean that the same peripheral (mid-brain) inhibition mechanism was operative in these tasks, with inhibition only being evoked later in the selective task (see section 3.4.2 for details). However, the notion of a non-cortical inhibition mechanism has been challenged, with the current view suggesting that, while the manifestation of inhibition may occur outside the cortex, the site and agent of inhibition involves an integrated network of the PFC, thalamus, basal ganglia, and motor cortices (Band & van Boxtel, 1999; van Boxtel et al., 2001, see section 3.4.1).

ERP correlates of inhibitory processing during the simple stop-signal task have provided some insight to date. The N1 component reflects the trial-to-trial variation of energy impinging on the auditory cortex (Näätänen & Picton, 1987), and has been shown to be overlapped by the attention-sensitive, fronto-central PN that may reflect an early discrimination process which rapidly processes the sensory attributes of a stimulus (Hillyard & Hansen, 1991; Näätänen & Michie, 1979). Therefore, any effect that the additional stimulus discrimination in the selective inhibitory response may have on perceptual processes should manifest in the N1 component. Specifically, if selective inhibition involves longer perceptual processing, N1 may be delayed in the selective compared to simple condition.

Due the inconsistent appearance of the N2 component between subjects in Study I (Chapter 4), the P3 component may be a more reliable index of auditory-evoked inhibitory processing in the stop-signal task (Bekker et al., 2005a; de Jong et al., 1990;



Kok et al., 2004). It was expected that if P3 peaked later in the selective than simple condition, this, as well as longer a SSRT, would support the notion of a slower inhibition process in this condition, while topographic differences between conditions would indicate distinct inhibition processes. However, mean amplitude in the 200 – 250 ms latency range, corresponding to typical SSRT in young, non-clinical adults, was used as a measure of N2 in order to examine whether the additional stimulus discrimination for the selective inhibitory response may affect processing within this interval.

The aim of the present study was to examine the effect of stimulus discrimination on the stop-signal response through behavioural and electrophysiological indices of inhibition, using a within-subject comparison of simple and selective stopping. An important methodological concern in the stop-signal task is the setting of the stop-signal delay, as this influences the stage at which the inhibition process acts upon response processing, and therefore affects stop-signal ERP averages. Therefore, the stop-signals were presented at set intervals preceding each individual's expected point of response execution, which provided ERP averages that capture relatively equivalent stages of response processing *between* subjects. It was predicted that if selective stopping affected the latency of perceptual or inhibitory processes, this would manifest in delayed N1 and/or P3 peaks, respectively, as well as a longer SSRT, in the selective compared to simple condition. Furthermore, it was predicted that, if simple and selective stopping were associated with spatially-distinct cortical inhibitory processes, this would manifest in different topography of the inhibition-related P3 component. Alternatively, a lack of such differences would suggest the use of the same fast and non-selective inhibitory response in both simple and selective conditions.

### 5.3 Method

#### 5.3.1 Subjects

Forty-three (22 female) aged 18 years 8 months to 39 years 11 months (mean age = 24.8 years, SD = 6.7 years) were included in this study. All subjects participated as a means of partially satisfying requirements in an undergraduate psychology course. Subjects were included if they received a standardised score of 80 or greater on the RPM (Raven, 2000) (mean = 116.1, SD = 14.4), and if they had never suffered an epileptic seizure, serious head injury, period of unconsciousness or any psychiatric condition. Each subject reported no problems with hearing, had normal or corrected-to-normal vision and were native English speakers. Informed consent was obtained from all subjects after the testing equipment had been explained, with the option to withdraw without penalty.

#### 5.3.2 Stop-signal Task

The stop-signal task consisted of a simple and selective condition, with presentation order counterbalanced between subjects. In both conditions, the primary task was a binary-selective RT task where visual “go” stimuli, consisting of cartoon pictures of a lion or an apple (3 cm high x 2 cm wide), were presented sequentially in the center of a 14 inch computer monitor at a viewing distance of 1 m at eye-level. Each trial lasted 2.5 s, consisting of a central fixation cross for 500 ms followed by the go stimulus for 2 s, allowing subjects 1.5 s to respond. Digits II and III of the right hand were used to respond by pressing one of two buttons on a computer keyboard, which were marked with the words *apple* (Alt key) and *lion* (Ctrl key).

The stopping component of the task differed between the simple and selective conditions. In the simple condition, a 1500 Hz tone was presented on 30 % of trials and acted as a *stop-signal*, instructing subjects to inhibit their response to the primary task. In the selective condition, the same 1500 Hz tone acted as the stop-signal on 30 % of trials, while a 1000 Hz tone was presented on a different 30 % of trials and acted as an *ignore-signal*, with subjects instructed to ignore that tone and continue responding. This resulted in an equal proportion of stop trials between conditions. Both tones were presented binaurally over headphones for 100 ms (rise and fall time 10 ms), at an intensity of 60 dB SPL, and occurred an equal number of times for each go stimulus. See Study I (Chapter 4) for the setting of the stop-signal delay. Briefly, stop-signal delay was presented at one of five variable delays, set relative to Go MRT from the preceding block. The same procedure was also applied for calculating the delay between go stimuli and ignore-signals.

### 5.3.3 Procedure

Subjects began by completing the RPM (Raven, 2000) and an information sheet used to screen for stimulant use and history of health concerns. In the laboratory, each subject was familiarised with the testing equipment and procedure. After equipment fitting, subjects were seated in a sound-attenuated testing room where they completed the condition of the stop-signal task. Each condition included one practice block and three experimental blocks consisting of 50 trials each. Time was taken to ensure that instructions were well understood. In both conditions, subjects were told to respond quickly and accurately to the presentation of visual go stimuli, and to withhold that response if they heard the stop-signal. In the selective condition, subjects were given the additional instruction that a lower-pitched tone would occur on some trials, but that

they should ignore this tone, and continue responding. Emphasis was placed on speed and accuracy for primary task performance, rather than successful stop. Subjects were told they should not wait for the tones as they would be unable to inhibit their response on every trial. It was explained that the onset of the stop- and ignore-signals was dependent upon their RT to the primary task, such that delaying responses would only delay the presentation of the tones in subsequent blocks. MRT was displayed on the screen after each block, allowing subjects to rest briefly and to track their response speed, and also allowing the experimenter to monitor subjects for response-delaying strategies. In this instance, the experimenter emphasised the necessity for fast responding, and instructed the subject to attempt to obtain a shorter MRT in the next block.

#### *5.3.4 Electrophysiological Recording*

All details for the recording of ERPs in this study are as outlined in Study I (Chapter 4). In brief, EEG was recorded from 17 sites of the International 10-20 system.

#### *5.3.5 Data Analysis*

##### **5.3.5.1 Performance measures**

In addition to the measures outlined in Study I (Chapter 4), the inhibition function, which plots inhibition probability at each stop-signal delay, was also measured. Correction of the inhibition function was subsequently performed to remove differences between conditions due to go response variability, whereby inhibition probability was plotted as a function of ZRFT ( $ZRFT = [Go\ MRT - stop\text{-}signal\ delay - SSRT] / Go\ SD$ ; Logan, 1994). To analyse differences in overall inhibition probability

between conditions across the five stop-signal delays a weighted average was calculated for each individual according to the frequency of stop-signals at each stop-signal delay.

Repeated measures ANOVAs were used to analyse all behavioural measures with Condition (simple, selective) as a within-subjects factor. Analysis of the inhibition function included Delay as an additional within-subjects factor. Planned contrasts compared data from (MRT – 0) through to (MRT – 450) ms using planned orthogonal polynomial contrasts.<sup>22</sup>

### 5.3.5.2 Event-related Potentials

The ERP epoch was defined as 100 ms pre-stimulus to 900 ms post-stop-signal onset. Epochs were randomly excluded for successful and failed stop trials to obtain approximately equal numbers between trial-types and conditions for each individual (mean = 16.3, SD = 7.3). ERP averages were subsequently computed for successful and failed stop trials in the simple and selective conditions.

Grand average ERP waveforms were displayed for the purpose of defining each component. A large N1/P3 complex was observed in all ERP averages, and a smaller P2/N2 complex was observed in most averages. Peak amplitudes were quantified for the N1 (80 to 190 ms) and P3 (260 to 450 ms) components as the maximum points in the large negative-positive complex by means of an automatic peak-picking program, using Scan software (Neuroscan, v4.2), relative to the 100 ms pre-stimulus baseline period. Peak latencies were fixed across all sites to the peak latency of the site of maximum amplitude, which was Cz for both N1 and P3 (Picton et al., 2000; Spencer,

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<sup>22</sup> As there were 26 subjects in the simple condition and 16 subjects in the selective condition who did not receive stop-signals at the (MRT- 600) ms delay, this variable was excluded from the inhibition function analysis.

Dien, & Donchin, 2001). The P2/N2 complex was small in magnitude and appeared inconsistently in the ERP averages.<sup>23</sup> This is common for auditory-evoked ERPs, where the P2/N2 is often overlapped by the N1 and P3 components (Fabiani & Friedman, 1995). However, the N2 has consistently been linked with inhibitory processes, even in the auditory modality (Falkenstein et al., 1999; Falkenstein et al., 1995b), while the 200 to 250 ms interval post stop-signal onset corresponds to estimations of SSRT in non-clinical adults. Therefore, mean amplitude was quantified in the 200 to 250 ms latency range to correspond to the N2 component.

Statistical analysis was restricted to data collected from nine sites (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) as this allowed a topographic analysis in terms of a 3 x 3 (Laterality by Sagittal) matrix following Pfefferbaum, Ford, White and Roth (1989). Repeated measures ANOVAs were used to analyse ERP amplitudes with the following within-subject factors: Laterality [Left (F3, C3, P3); Midline (Fz, Cz, Pz); Right (F4, C4, P4)] and Sagittal [Frontal (F3, Fz, F4); Central (C3, Cz, C4); Parietal (P3, Pz, P4)] examining topography, Condition (simple versus selective) and Trial (successful stop versus failed stop). Planned contrasts within the Sagittal factor compared the frontal and parietal regions, and the mean of these with the central region, while comparisons within the Laterality factor compared the left and right hemispheres, and the mean of these “lateral” regions with the midline. These planned contrasts provide optimal information on the topographic distribution of the amplitude of each component. Analyses for component peak latency excluded site contrasts. As all contrasts were planned and there were no more of them than the degrees of freedom for effect, no Bonferroni-type adjustment to  $\alpha$  was necessary (Tabachnick & Fidell, 1989). Also,

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<sup>23</sup> Fifteen subjects did not show a P2/N2 complex in at least one ERP average waveform (i.e. out of four).

the single degree of freedom contrasts are not affected by violations of symmetry assumptions common in repeated measures analyses, and thus do not require Greenhouse-Geisser type corrections. In order to interpret scalp distributions within Condition and Trial, the data were normalised with the vector scaling method, using the square root of the average of squared across-subjects mean amplitude (McCarthy & Wood, 1985), and only topographic interactions that remained significant after normalisation are reported. Unless otherwise indicated, degrees of freedom for all statistical effects reported are (1, 42).

## 5.4 Results

### 5.4.1 Performance Measures

Table 5.1 provides the means and effect summaries for the performance measures. SSRT did not differ between the simple and selective conditions ( $F < 1$ ). Go MRT was longer ( $F = 6.8, p < .05$ ), and the likelihood of committing an omission error greater ( $F = 8.6, p < .01$ ), in the selective than simple condition, with no between-condition difference for choice errors ( $F = 1.0, p = .324$ ). Accuracy of responding on ignore-signal trials was high at 93.2 % (SD = 8.5 %), and mean RT (IGRT; mean = 721.5; SD = 183.5 ms) was 120.2 ms longer than for no-signal trials ( $F = 133.6, p < .001$ ). Mean RT for failed stop trials (FSRT) was shorter than no-signal trials in the simple condition, and somewhat longer than no-signal trials in the selective condition ( $F = 5.0, p < .05$ ).

**Table 5.1. Means and standard deviations of behavioural measures for simple and selective conditions.**

Condition	Go MRT	Omission errors	Choice errors	SSRT	FSRT
Simple	561.7 (113.8)	0.8 (0.9)	1.0 (1.3)	230.4 (64.8)	534.7 (97.5)
Selective	601.7 (138.9)	4.0 (6.9)	41.3 (1.9)	230.0 (83.1)	609.8 (146.6)

**Notes:** (1) Go MRT = Mean reaction time to go stimuli on no-signal trials; SSRT = Mean stop-signal reaction time; FSRT = Mean reaction time to go stimuli on failed stop trials; IGRT = Mean reaction time to go stimuli on ignore-signal trials; (2) reaction times in milliseconds; (3) errors in percentages.

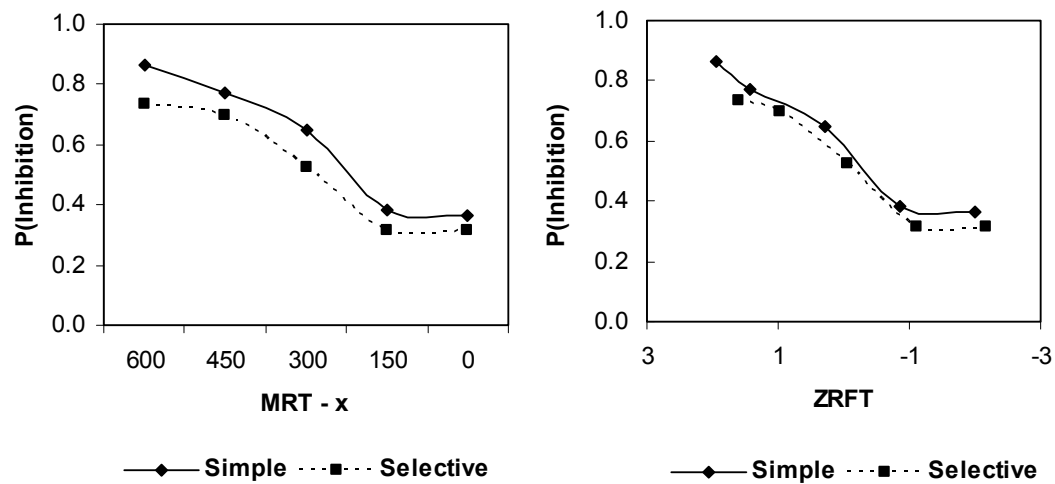
Figure 5.1 (left panel) shows the inhibition functions across stop-signal delay for each condition. Across conditions, inhibition probability showed linear ( $F = 156.0$ ,  $p < .001$ ) and quadratic effects ( $F = 9.4$ ,  $p < .01$ ). Condition did not interact with Delay, however, indicating that slopes of the inhibition functions were similar between conditions. Across the five stop-signal delays, average inhibition probability was found to be larger in the simple than selective condition ( $F = 7.1$ ,  $p < .05$ ). Plotting inhibition probability as a function of ZRFT appeared to align the inhibition functions (see Figure 5.1, right panel).<sup>24</sup>

A pearson's bivariate correlation was performed to examine whether simple and selective conditions shared a similar source of variance in inhibition probability. Band (1997, Chapter 3) states that the inhibition probability of conditions that access the same inhibition process should be correlated. The correlation between conditions was found to be significant ( $r = .51$ ,  $p < .01$ ,  $r^2 = 25.8\%$ ).

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<sup>24</sup> Because the abscissae for the two data sets do not correspond, one cannot test for alignment statistically (Hanes & Carpenter, 1999).

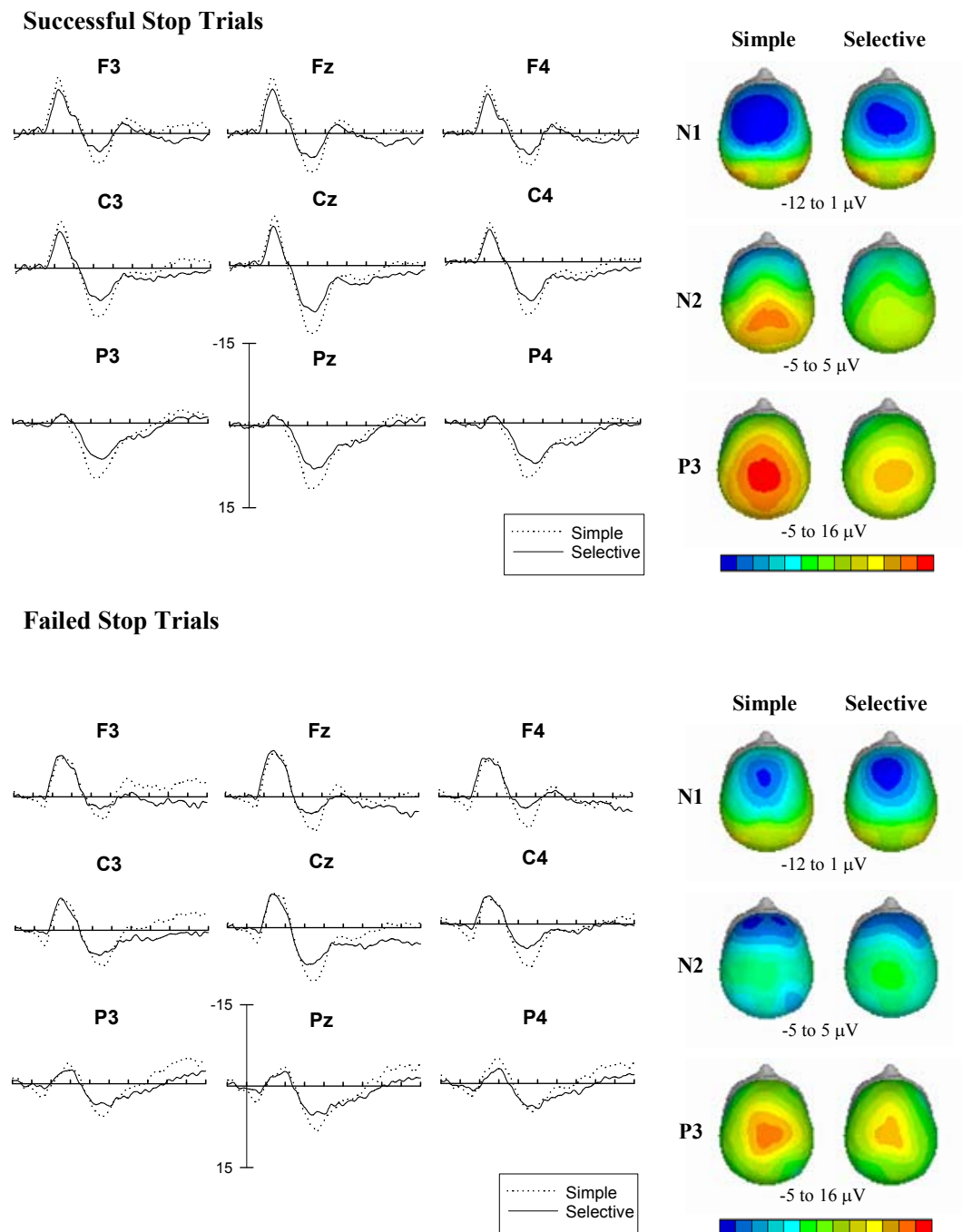




**Figure 5.1. Inhibition probability as a function of stop-signal delay (MRT – x) (left panel) and as a function of ZRFT (right panel). Note: There were 12 subjects who obtained a stop-signal at the (MRT – 600) ms delay.**

#### 5.4.2 Stop-signal ERP Waveform Morphology

Figure 5.2 depicts the ERP average waveforms and topographic maps for successful versus failed stop trials in the simple (upper panel) and selective conditions (lower panel). A large N1-P3 complex was evident for both successful and failed stop trials, corresponding to previous studies using auditory stop-signals in adults (de Jong et al., 1990). The N1 (peak latency 132 ms) appears to be largest in the fronto-central region, while the centro-parietal P3 (336 ms) was similar in distribution to the novelty P3, previously reported for novel tones in the oddball task (Fabiani & Friedman, 1995; Spencer et al., 2001). Although a centrally-maximal P2 (194.2 ms) was observed in most individual waveforms, the component was not evident in the grand averages due to its small magnitude. Similarly, a frontally-maximal N2 (206 ms) was found in most individual waveforms, but can be observed in the grand averages for successful stop trials at frontal sites on descending flank of the N1. For failed stop trials, the N1 and N2 were not dissociable, appearing as a broad negativity, although at parietal sites, the N2 is clearly evident.



**Figure 5.2.** Grand average stop-signal ERP waveforms and topographic maps comparing the simple (solid) and selective conditions (dotted) for successful (top panel) and failed stop trials (bottom panel). Notes: (1) Dashes on the x-axis = 100 ms, (2) stimulus onset is indicated by vertical bar, (3) y-axis =  $\pm 15 \mu\text{V}$  (shown at Pz), and (4) negative-going amplitude is up.

### 5.4.3 Overall Stop-signal ERP Component Analysis

These effects describe the maximum amplitudes within the contrasts performed, across Trial and Condition (see Table 5.2 for means and effect summaries). N1 showed left-midline, fronto-central maximas, with the left > right effect largest in the fronto-central region and the midline > lateral effect largest centrally. Mean N2 amplitude showed lateral and frontal maximas, with the lateral > midline effect largest in the central region. P3 showed midline, centro-parietal maximas, with the midline > lateral effect largest in the central region.

**Table 5.2. A summary of ERP component amplitude analyses and means results across Trial and Condition.**

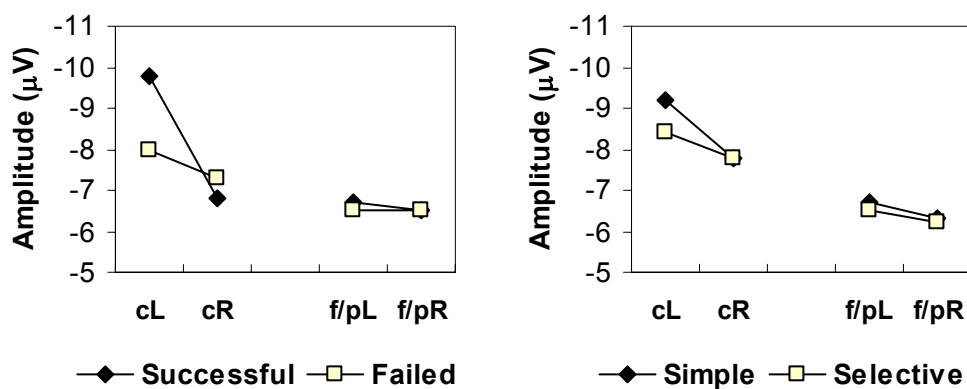
	Effect	Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>N1</b>	Lat	L vs. R	-7.3 vs. -6.8	5.5	.023
		M vs. L/R	-8.4 vs. -7.1	118.1	.000
	Sag	f vs. p	-10.3 vs. -3.3	112.6	.000
		c vs. f/p	-9.0 vs. -6.8	112.8	.000
	Lat x Sag	fL to fR vs. pL to pR	-10.3 to -9.5 vs. -2.9 to -3.0	14.7	.000
		cL to cR vs. f/pL to f/pR	-8.8 to -7.8 vs. -6.6 to -6.3	11.5	.002
		cM to cL/R vs. f/pM to f/pL/R	-10.5 to -8.3 vs. -7.4 to -6.4	30.2	.000
<b>N2</b>	Lat	M vs. H	-0.3 vs. -1.0	22.1	.000
	Sag	f vs. p	-2.7 vs. 0.2	22.5	.000
		c vs. f/p	0.2 vs. -1.3	35.9	.000
	Lat x Sag	cM to cL/R vs. f/pM to f/pL/R	0.9 to -1.3 vs. -1.0 to -1.4	8.4	.006
<b>P3</b>	Lat	M vs. H	11.0 vs. 8.3	175.4	.000
	Sag	f vs. p	7.6 vs. 9.0	4.3	.044
		c vs. f/p	11.1 vs. 8.3	138.1	.000
	Lat x Sag	cM to cL/R vs. f/pM to f/pL/R	13.9 to 9.7 vs. 9.6 to 7.7	141.5	.000

**Abbreviations:** for this and subsequent tables, vs. = versus; Sagittal (Sag): f = frontal (mean activity at F3, Fz and F4); c = central (mean activity at C3, Cz and C4); p = parietal (mean activity at P3, Pz and P4); f/p = frontal/parietal (mean activity of F3, Fz, F4, P3, Pz and P4); Laterality (Lat): L = left (mean of activity at F3, C3 and P3); R = right (mean of activity at F4, C4 and P4); M = midline (mean of activity at Fz, Cz and Pz); L/R = left/right (lateral regions; mean of activity at F3, F4, C3, C4, P3 and P4); Lateral by Sagittal interactions: fL = F3; fR = F4; fM = Fz; fL/R = mean of activity at F3 and F4; cL = C3; cR = C4; cM = Cz; cL/R = mean of activity at C3 and C4; pL = P3; pR = P4; pM = Pz; pL/R = mean of activity at P3 and P4; f/pL = mean of F3 and P3; f/pR = mean of activity at F4 and P4; f/pM = mean of activity at Fz and Pz; f/pL/R = mean of activity at F3, F4, P3 and P4.

#### 5.4.4 Trial and Condition Effects

These effects show maximum amplitude within the contrasts performed that differ between successful and failed stop trials across conditions (see Table 5.3 for means and effect summaries), and that interact with conditions (see Table 5.4 for means and effect summaries).

**N1:** Across conditions, successful stop trials showed a central > frontal/parietal effect that was reduced for failed stop trials. Furthermore, a left > right effect that was maximal in the central region was larger for successful compared to failed stop trials (see Figure 5.3, left panel). Between conditions, a centrally-maximal left > right effect also occurred in the simple condition, while amplitude was relatively equipotential across the lateral region in the selective condition (see Figure 5.3, right panel). With respect to latency, N1 peaked earlier for successful compared to failed stop trials.



**Figure 5.3.** N1 amplitude for successful versus failed stop trials (left panel) and in the simple versus selective condition (right panel) at the left and right hemispheres for the central and frontal/parietal regions. Note: negative-going amplitude is up.

**Table 5.3. A summary of ERP component amplitude and latency analyses results for Trial effects. Notes: (1) the “Successful stop” and “Failed stop” columns indicate the means for each trial-type. Notes: (1) See Table 5.2 for abbreviations; also T = Trial, (2) all amplitude values in  $\mu\text{V}$ , (3) all latency values in ms.**

	Effect	Contrast	Successful stop (SS)	Failed stop (FS)	<i>F</i>	<i>p</i>
<b>Amplitude</b>						
<b>N1</b>	T x Sag	c vs. f/p	-9.8 vs. -6.8	-8.3 vs. -6.8	52.8	.000
	T x Lat x Sag	cL to cR vs. f/pL to f/pR	-9.6 to -8.4 vs. -6.7 to -6.5	-8.0 to -7.3 vs. -6.5 to -6.5	10.6	.002
<b>N2</b>	T	SS vs. FS	0.6	-2.2	12.1	.001
	T x Lat	L vs. R	0.1 vs. 0.6	-2.1 vs. -2.6	10.6	.002
	T x Sag	f vs. p	-1.7 vs. 2.3	-3.7 vs. -1.9	10.9	.002
		c vs. f/p	1.3 vs. 0.3	-0.9 vs. -2.8	11.1	.002
	T x Lat x Sag	cM to cL/R vs. f/pM to f/pL/R	2.3 to 0.8 vs. 0.6 to 0.1	-3.6 to -3.8 vs. -2.6 to -3.0	6.1	.018
<b>P3</b>	T	SS vs. FS	10.3	8.2	4.2	.048
	T x Sag	f vs. p	7.9 vs. 10.9	7.4 vs. 7.0	18.1	.000
<b>Latency</b>						
<b>N1</b>	T	SS vs. FS	128.2 ms	136.0 ms	8.1	.007

**Table 5.4. A summary of ERP component amplitude analyses results for Condition effects. Notes: (1) the “Simple” and “Selective” indicates the means for each condition. Notes: (1) See Table 5.2 for abbreviations; also, C = Condition.**

	Effect	Contrast	Simple	Selective	<i>F</i>	<i>p</i>
<b>N1</b>	C x Lat x Sag	cL to cR vs. f/pL to f/pR	-9.2 to -7.8 vs. -6.7 to -6.3	-8.4 to -7.8 vs. -6.5 to -6.2	6.7	.013
			SS: -2.1 vs. 3.1	SS: -1.3 vs. 1.5		
<b>N2</b>	C x T x Sag	f vs. p	FS: -3.8 vs. -2.5	FS: -3.7 vs. -1.4	7.6	.008
			SS: 2.7 to 1.0 vs. 0.7 to 0.3	SS: 1.9 to 0.6 vs. 0.6 to -1.1		
	C x T x Lat x Sag	cM to cH vs. f/pM to f/pH	FS: -0.8 to -0.2 vs. -2.8 to -3.3	FS: -0.2 to -1.0 vs. -2.3 to -2.6	10.3	.003
<b>P3</b>	C	Simple vs. Selective	10.2	8.2	7.1	.007
	C x Lat	M vs. Lat	12.3 vs. 9.2	9.7 vs. 7.5	8.5	.006

**N2:** Across condition, N2 amplitude was larger for failed compared to successful trials across the scalp, and this difference was maximal in the parietal region and minimal in the central region. Furthermore, successful stop trials showed a left > right effect while failed stop trials showed the converse; this lateral effect did not differ across the sagittal region for successful stop trials, but was minimal in the central region for failed stop trials. Between conditions, successful stop trials showed a frontal > parietal effect that was larger in the simple than selective condition; this condition difference was reduced for failed stop trials (see Figure 5.2). Furthermore, a centrally-maximal lateral > midline effect for successful stop trials did not differ between conditions; for failed stop trials, this effect occurred in the selective condition only (see Figure 5.2).

**P3:** Across conditions, P3 amplitude was larger for successful compared to failed trials across the scalp, and this difference was largest in the parietal region. Between conditions, P3 amplitude was larger in the simple compared to selective condition across the scalp (see Figure 5.2), and this difference was largest in the midline region.

## **5.5 Discussion**

The present study examined whether an additional stimulus discrimination to the stop-signal response in the selective stop-signal task would be associated with a slower inhibitory response, distinct inhibitory processing, or both. Additive effects on the stop-signal response were expected to manifest in a longer SSRT and increased ERP peak latencies in the selective compared to simple condition, particularly for the early sensory discrimination process reflected in N1 or the inhibition-related P3. Evidence of different inhibition processes between conditions was expected to manifest in different topographic distributions of the P3 component.

### 5.5.1 Performance

The race model states that go and inhibition processes are independent (Logan, 1994), suggesting that manipulations of the inhibitory response in the selective condition should not have affected performance of the response process. Nevertheless, longer Go MRT for no-signal trials and a greater probability of committing an omission error were found in the selective compared to simple condition. This suggests that the greater number of trials containing a tone in the selective condition may have encouraged subjects to adopt a cautious response style, slowing down responses to increase the likelihood of stopping a response. Previous reports have shown that increasing the number of stop-signals results in subjects increasing RT (Logan & Burkell, 1986). Although the ignore-signal was not relevant to the task, mean RT on these trials was 120 ms longer than that on no-signal trials, revealing that the detection of an auditory stimulus caused a temporary interruption to response processing (McGarry et al., 2003). This difference probably reflects the time taken to identify that the validity of the tone and then re-engage response processes. Therefore, these findings suggest that increasing the number of trials containing a tone, regardless of whether the tone is a valid stop-signal or not, fosters a cautious response style (see also Chapter 7).<sup>25</sup>

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<sup>25</sup> These findings suggest that the independence assumption was violated in the selective condition, which may cause an underestimation of SSRT. As a test of this assumption, the model predicts that mean RT on failed stop trials should be faster than on no-signal trials. This prediction was upheld in the simple condition, but not in the selective condition. However, Band et al. (2000) suggest that these violations do not affect SSRT estimated using the method in the present study. Furthermore, as SSRT differences between conditions were statistically non-significant at  $F < 1$ , even a large underestimation would not alter the  $F$ -value to produce a significant result, supporting the current findings.

With respect to the latency of the inhibitory response, estimated mean SSRT did not differ between conditions. This finding is in contrast to the two previous studies examining selective inhibition through discrimination between stop-signals. However, the present study differs from these previous studies in a number of respects. For example, Bedard et al. (2002) suggested they found longer SSRTs in a selective stop-signal task, relative to a similarly designed study examining simple inhibition (Williams et al., 1999), however, the present finding is more compelling because of the within-subject comparison between simple and selective conditions. Riegler (as cited in Logan, 1994) used two tones in the simple and selective conditions, with subjects stopping to both tones in the simple condition and to only one tone in the selective condition. Presenting two stop-signals in a task may have resulted in a faster inhibitory response in the simple condition, or alternatively, subjects may have found it more difficult to discriminate between valid and invalid tones in the selective condition if both tones were valid in the previous condition. Studies where the inhibitory response is dependent upon discrimination between go stimuli, as opposed to stop-signals, have also shown longer SSRT for selective compared to simple inhibition conditions (Logan et al., 1986; Van den Wildenberg, 2003), however, this difference has been shown to be due to subjects being unable to engage the inhibitory response until response selection has been completed for the primary task (de Jong et al., 1995).

Similar stopping times between simple and selective conditions suggests that the activation of a similar fast and non-selective inhibitory response. This is also supported by the significant correlation of inhibition probability between conditions, which suggested that the two conditions shared a similar source of variance in inhibition probability, and therefore, may have accessed the same inhibition process (Band, 1997, Chapter 3). Furthermore, similar stopping times between conditions suggests that



stimulus discrimination occurred in parallel with inhibitory processing (de Jong, 1992), as opposed to beginning only after the completion of the preceding stage, as is the case with sequential processing (Segalowitz, 2000). Van den Wildenberg and van der Molen (van den Wildenberg & van der Molen, 2004a) manipulated the difficulty of stop-signal discrimination and found that SSRT was unaffected unless the discrimination was extremely difficult. Therefore, the latency of the inhibitory response appears to remain relatively unaffected by manipulations of stop-signal discrimination.

Although slower responses are typically easier to inhibit (Logan, 1994), inhibition probability was reduced in the selective condition, in line with previous within-subject findings (Logan & Burkell, 1986; van den Wildenberg & van der Molen, 2004). The race model allows a dissociation of five factors mediating inhibitory performance, including: a fast or variable go process, a slow or variable inhibition process, or the triggering rate of the inhibition process. An examination of the inhibition function can provide an insight into the effect of these variables on inhibitory performance (Logan, 1994; Logan et al., 1984). The inhibition function was reduced in the selective compared to simple condition similarly across all stop-signal delays. However, when inhibition probability was plotted as a function of ZRFT, that is, the transformation of the relative finishing time between the go and inhibition responses, the inhibition functions appeared to be brought into alignment. This transformation takes into account Go MRT and variability, as well as SSRT. As SSRT did not differ between conditions and Go MRT was slower (not faster) in the selective condition, this rules out the speed of the go and inhibition processes as the cause. Rather, reduced inhibition probability in the selective task may be accounted for by differences in go response variability, rather than differences in inhibitory control.

### 5.5.2 *Event-related Potentials*

In the simple condition, the fronto-central N1 was larger for successful compared to failed stop trials, which is consistent with recent findings (Bekker et al., 2005a). The N1 is an early component associated with the sensory discrimination of stimuli and is believed to reflect the impact that auditory input has on the auditory cortex, which varies trial-to-trial (Näätänen & Picton, 1987). It was predicted that if stimulus discrimination in the selective inhibitory response increased the latency of perceptual processing, this would be reflected in a delayed N1. However, N1 peak latency did not differ between conditions, supporting the SSRT finding and the notion that sensory discrimination of stop- and ignore-signals occurred in parallel with inhibitory processes (Logan, 2002).

Bekker et al. (2005a) suggests that enhanced N1 amplitude on successful stop trials reflects greater attention to the stop signal that is determinative for the quality of inhibitory control, itself reflected in the stop P3. The present findings showed a shorter N1 peak latency and enhanced amplitude in the central region, particularly in the left hemisphere, for successful compared to failed stop trials. These effects may reflect a greater attention-effect associated with enhanced discrimination of stimulus features that facilitates subsequent successful inhibition. This interpretation is strengthened by the finding of a similar effect between conditions, with the simple condition showing a centrally-maximal left > right effect relative to the selective condition. The switch from a long period of silence to an auditory stimulus in the simple condition may impinge more energy on sensory channels than the switch from a tone of one frequency to a tone of another, as was the case in the selective condition, resulting in N1 amplitude (Näätänen & Picton, 1987). Therefore, having to discriminate between two tones, as opposed to one, served to reduce the effectiveness of the stop-signal in attracting

attention necessary for further inhibitory processing, although this was not directly related to the selective nature of inhibition in this condition, but to the context of stimulus presentation. While it may be claimed that greater left-central N1 activity in the simple condition merely reflects the difference in the proportion of trials containing an auditory stimulus (i.e. larger amplitude for rarer events), the similar enhancement for successful stop trials argues against this possibility as the proportion of successful stop trials across conditions was greater than failed stop trials.

The frontal N2 for successful stop trials has been associated with a frontal inhibition process in the past (Eimer, 1993; Jodo & Kayama, 1992; Kok, 1986), but more recently, has been associated with the detection of conflict between concurrently activated responses (Nieuwenhuis et al., 2003). Mean N2 amplitude in the 200 to 250 ms interval showed a frontal maximum, as well as the typical enhancement for failed compared to successful trials across the scalp. However, this trial-type difference was largest in the midline and fronto-central regions, corresponding well with the response-locked Ne. The Ne has a midline, fronto-central maximum and shows greater amplitude after erroneous than correct responses (Gehring et al., 1993), suggesting that the stimulus-locked N2 on failed stop trials may be overlapped by the response-locked Ne (Hajcak, Vidal, & Simons, 2004). This issue is further examined in the next study (see Chapter 6).

N2 amplitude for successful stop trials showed a different distribution between conditions, suggesting differential inhibitory processing. Successful stop trials showed a frontal > parietal N2 gradient effect in the simple condition, while amplitude in the selective condition was more diffuse across frontal and parietal regions. Furthermore, N2 in the simple condition showed a centrally-maximal lateral > midline effect for successful stop trials that was reduced in the selective condition. As processes related

to the discrimination between stop- and ignore-signals did not increase stopping latency, but occurred in parallel with inhibitory processing, it is suggested that the more distributed network of N2 activity found in the selective condition reflects the recruitment of these additional processes (i.e. stimulus discrimination, response selection and working memory). This finding corresponds with previous research showing the activation of a widely distributed network when the decision to inhibit was dependent upon accessing working memory (Garavan et al., 1999; Mostofsky et al., 2003).

The timing and activation of the inhibition processes was investigated through an examination of the centro-parietal P3 component, which has been implicated as reflecting the inhibition process in the stop-signal task (de Jong et al., 1990; Kok et al., 2004). In the present study, P3 showed the typical enhancement for successful compared to failed trials (Bekker et al., in press; de Jong et al., 1990; Dimoska et al., 2003), which was largest in the centro-parietal region, supporting its relation to a stop-signal inhibition process. In line with a similar SSRT between simple and selective conditions, P3 peak latency did not differ between conditions, suggesting similar inhibition processes. It was also predicted that, if simple and selective inhibition were associated with spatially-divergent inhibition processes, this would manifest in different distributions of P3 activity across the scalp. However, simple stopping merely showed a greater  $\text{midline} > \text{left/right}$  effect compared to selective stopping, which does not correspond with current notions of a fronto-central (De Jong et al., 1990) or central (Kok et al., 2004; Ramautar et al., 2004) inhibitory source. Therefore, there was evidence of differential engagement of inhibitory processing between simple and selective inhibition (N2), however, ultimately, responses were stopped using the same

fast, non-selective, inhibition process in the simple and selective conditions (de Jong et al., 1995), as reflected in stop P3.

Across the scalp, larger P3 amplitude was found in the simple compared to selective condition. This may reflect a greater degree of inhibitory activation in the simple condition, however, it should also be stressed that the P3 amplitude in other tasks has been shown to increase with the subjective probability of an event (Duncan-Johnson & Donchin, 1977); larger P3 amplitude in the simple condition may reflect the rarer occurrence of an auditory stimulus.

Within motor-related research, findings show that subjects can activate a motor response even before stimulus evaluation is complete (e.g. Coles 1985, 1988; Gratton et al., 1988; Smid et al., 1992). This is a strategy adopted by some subjects which results in quicker responses, although the trade-off is an increase in errors. Similarly, subjects in the present study appeared to adopt the strategy of “stop first, think later”, activating the inhibition process as soon as an auditory stimulus was detected in order to increase chances of successful stop, and then continuing stimulus evaluation. This is the more efficient inhibition strategy, as opposed to discriminating first, and then inhibiting later.

### 5.2.3 *Limitations*

A limitation of this study was that that some subjects appeared to prolong responses despite repeated instructions to respond quickly in order to increase chances of a successful stop. This resulted in a large variability in Go MRT between subjects for all trial-types, which may have affected average stop-signal ERPs. For example, subjects who respond faster will find it more difficult to inhibit their responses on a stop-signal trial compared to slower subjects, and may require greater (or faster) activation of the inhibition process to successfully inhibit a response. This will manifest

as enhanced amplitude (or shorter peak latencies) of the component reflecting the inhibition process, relative to slow subjects. Therefore, the next study in this thesis will attempt to disentangle the effects of subjects' response strategy on ERPs, and utilise this as a method of further investigating the functional significance of components (see Chapter 6). Secondly, a further limitation of this study was that 30 % of trials included a tone in the simple condition, contrasting with the 60 % of trials in the selective condition. Although stop- and ignore-signals differed in pitch, P3 amplitude may be reflecting a global response to the number of auditory stimuli (so-called "global" auditory stimulus probability). P3 amplitude has been shown to display an inverse relationship with the *subjective* probability of an event (Duncan-Johnson & Donchin, 1977). Furthermore, the LRP was not able to be examined in the present study as subjects were instructed to use one (dominant) hand, and calculation of the LRP requires the subtraction of activity from contralateral hemispheres for both hands (this was rectified for later studies).

#### 5.5.4 *Summary*

In summary, the effect of including a stimulus discrimination to the inhibitory response in the selective stop-signal task, where subjects are asked to discriminate between stop- and ignore-signals, did not increase the latency of the inhibitory response, but did reduce inhibition probability. However, this latter effect was attributed to greater within-subject variability of the go response, rather than a deficiency of the inhibitory response. Similar peak latencies between conditions supported the hypothesis that the additional stimulus discrimination in the selective inhibitory response occurred in parallel with inhibitory processes, as reflected in the different distribution of N2 mean amplitude between conditions. Furthermore, while stop-signals

in the simple condition were associated with a greater N1 attention-effect, relative to the selective condition, this was a result of the context of stimulus presentation. However, the key finding in the present study was that the regional distribution of the stop P3 did not differ between conditions, suggesting that responses were inhibited using a similar fast, non-selective, inhibition process in simple and selective conditions.

Several important research questions were raised by the results of the present study. These questions relate to (a) the effect that adopting a fast or slow response style may have on use of particular inhibition strategies and processes, and (b) the functional role of the N2 component within stop-signal processing, (c) the nature of the inhibition process reflected in the P3 component, and (d) the effect of error-related components on failed stop trials. The most fundamental of these questions relates to the exact functional roles of the N2 and P3 components for successful and failed stop trials. Therefore, the primary aim of the next study is to address this issue through closer examination of the current selective stop condition, whereby stop-signal processes specifically related to the success and failure of inhibition will be isolated by comparing the “task-relevant” stop-signal ERPs with the “task-irrelevant” ignore-signal ERPs, in a group of fast versus slow responders.

## **6. Study III - The auditory-evoked N2 and P3 components in the stop-signal task: Indices of inhibition, response-conflict or error-detection?\***

### **6.1 Abstract**

The N2 and P3 ERP components have been separately associated with inhibitory processing in the stop-signal task, and more recently, the N2 has been implicated in the detection of response-conflict. The present study isolated processing related to successful and failed stopping through a comparison of responses to the stop-signal with those to a task-irrelevant tone in fast and slow RT groups. Relative to ignore-signals, stop-signals elicited a failed stop N2 and a successful stop P3. Between groups, it was hypothesised that greater inhibitory activation would be required to stop faster responses. Successful stop P3 showed the anticipated effect, supporting its association with urgent inhibitory control. N2 was enhanced in the slow group, and in contrast to the predictions of the response-conflict hypothesis, N2 and the response-locked error-negativity (Ne) differed in scalp distribution. The stop N2, therefore, may reflect a deliberate form of response selection, which the slow group employed as a means of increasing the likelihood of a successful stop. Finally, findings indicated that failed stop N2 and P3 were partially overlapped by Ne and error-positivity (Pe). These findings indicate a functional dissociation of stop N2 and P3 that is dependent upon the adoption of distinct performance strategies.

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\* Dimoska, A., Johnstone, S.J., & Barry, R.J. (submitted). The auditory-evoked N2 and P3 components in the stop-signal task: Indices of inhibition, response-conflict or error-detection? *Brain and Cognition*.



## 6.2 Introduction

Two ERPs in the stop-signal task that have been variably interpreted as reflecting response inhibition are the frontal N2, a negative potential peaking around 200 – 250 ms after the onset of the stop-signal, and the fronto-central P3, a positive component peaking at 300 – 350 ms. However, the functional significance of these components has not been settled unequivocally, particularly for the N2, which has recently been associated the detection of response-conflict in the go/nogo task (see section 3.5.1). In contrast, the P3 has been more consistently associated with inhibition in the stop-signal task, although the exact nature of this association is unclear (see section 3.5.2). Although functional interpretations of stop-signal ERPs have previously been borrowed from the go/nogo task, Study I (Chapter 4) found that N2 and P3 showed different topographic distributions between nogo and successful stop trials, implicating the activation of different underlying processes. This suggests that go/nogo interpretations of these components may not be entirely valid for stop-signal ERP effects. Therefore, the aim of the present study is to examine the response inhibition or response conflict hypotheses for stop N2 and P3, and the role of error-related processes on failed stop trials.

Typically, stop-signal studies compare ERPs on successful and failed stop trials. While this comparison is conceptually appropriate, differential processing has been found between successful and failed stop trials through different ERP scalp distributions (Dimoska et al., 2003), brain imaging (Rubia et al., 2003) and dipole source modeling (Kok et al., 2004). Successful stop trials contain activity related to the inhibition of a response, however, failed stop trials may also contain error-related activity. Therefore, a methodological objective of this study was to expand on previous attempts to isolate components specifically related to inhibitory processing. This was achieved by

comparing stop-signal ERPs for successful and failed stop trials with “task-irrelevant” ignore-signal trials, which were divided into fast and slow RTs corresponding to the failed and successful parts of the Go RT distribution (Logan, 1994). This approach likened the comparison of go and nogo trials (Falkenstein et al., 1999), or attend versus unattend conditions (Hohnsbein, Falkenstein, Hoorman, & Blanke, 1991), thereby creating a “task-relevant” versus “task-irrelevant” processing comparison. Therefore, ERP activity related to the processing of the preceding go stimulus and processes related to initial auditory stimulus registration that are common to both stop- and ignore-signals may be eliminated through statistical comparison. Furthermore, both auditory tones were presented with an equal probability, and therefore, oddball-type effects were also accounted for with this methodology.

In Study II (Chapter 5) performance and ERPs were compared between simple and selective inhibition conditions, with an observed limitation being the apparent prolonging of responses by subjects in the selective condition, despite instructions to respond quickly, in order to increase the likelihood of successful stop. Differential performance strategies may lead to differential activation of response inhibition processes as subjects with slower responses will find it easier to inhibit a response than subjects with faster responses, who may require greater or faster inhibitory activation to successfully stop a response. An analysis of RT on failed stop trials (FSRT) in the selective condition of Study II revealed an almost bimodal distribution of RTs, therefore, the sample was divided into two performance groups using a median-split, resulting in a “slow” group for subjects with slower FSRTs and a “fast group” for subjects with faster FSRTs. As outlined in section 3.6.4, adopting a particular response style may be associated with the activation of a distinct inhibitory network. The review of literature suggests that faster responses may activate an urgent inhibitory brake,

possibly associated with greater activation in the ACC, while slower responses may be associated with deliberate response selection in the dorsolateral PFC, as opposed to inhibition (Garavan et al., 2002; Kelly et al., 2004). With the above findings in mind, it was expected that slow responders would be more likely to utilise the response selection process, while fast responders would activate the urgent inhibitory brake to a greater extent, and that this would manifest in the components directly reflecting these processes as enhanced amplitude.

In summary, the primary aim of this study was to investigate the functional significance of the N2/P3 components for successful and failed stop trials. Firstly, task-relevant stop-signal ERPs were compared with task-irrelevant ignore-signal ERPs in order to isolate processing specifically related to the success and failure of inhibition. ERP activity that was common to both stop- and ignore-signal trials was eliminated through statistical comparison. Secondly, fast and slow RT groups were compared as it was hypothesised that faster responses, which are more difficult to stop than slower responses (Logan, 1994), would be associated with greater or faster inhibitory activation on successful stop trials, and manifest in the component reflecting this process. Finally, stop-signal locked N2 and P3 were examined in relation to response-locked Ne and Pe. Specifically, the response-conflict hypothesis states that successful stop N2 and Ne reflect activation of the same underlying process, and should therefore, display similar topographic distribution and behave similarly between RT groups. Furthermore, if N2/P3 for failed stop trials reflect aspects of response-related, error processing, a strong relationship was predicted with Ne and Pe.

## 6.3 Method

### 6.3.1 Subjects

Subjects were from Study II (Chapter 5), with one subject excluded randomly to obtain an equal number in the fast ( $n = 21$ ) and slow ( $n = 21$ ) RT groups. Thus, subjects included forty-two adults (22 female) aged 18 years and 10 months to 39 years 11 months (mean age = 24.8 years, SD = 6.7 years).

### 6.3.2 Stop-signal Task

All stop-signal task specifications in this study are as outlined in Study II (Chapter 5), although only data from the selective condition are presented here. In brief, subjects completed a visual primary, binary choice-RT task with auditory stop-signals (1500 Hz) presented on 30% of trials and ignore-signals (1000 Hz) presented on a different 30% of trials. Stop-signal delay was presented at one of five variable delays, set relative to Go MRT from the preceding block.

### 6.3.3 Procedure

All procedural details in this study are as specified in Study II (Chapter 5). In brief, subjects were asked to respond accurately and quickly to the primary task, and to inhibit responses when a stop-signal occurred, but to not wait for tones. All details for the recording of ERPs in this study are as outlined in Study I (Chapter 4). In brief, EEG was recorded from 17 sites of the International 10-20 system.

### 6.3.4 *Data Analysis*

#### **6.3.4.1 Performance Measures**

An analysis of failed stop RTs (FSRT) for the selective condition in Study II (Chapter 5) revealed an almost bimodal distribution of RTs, therefore, analyses were performed on the sample divided into two groups using a median-split, resulting in a slow group for subjects with slower FSRTs and a fast group for subjects with faster FSRTs. ANOVAs were used to compare differences between groups for all performance measures. All measures were as outlined in Study II. Additionally, the slope of each subject's inhibition function was calculated by fitting regression lines.

#### **6.3.4.2 Event-related Potentials**

Vertical EOG was subtracted from the EEG using the regression algorithm in the time domain outlined by (Semlitsch et al., 1986). Horizontal EOG was manually inspected for gross eye movements and epochs were rejected if they contained activity greater than  $\pm 200 \mu\text{V}$ . All epochs were baseline corrected using the pre-stimulus period. The ERP epoch was defined as 100 ms pre-stimulus to 900 ms post-stimulus onset for stimulus-locked ERPs and 500 ms pre-response to 500 ms post-response for response-locked ERPs. Epochs were randomly excluded until an equal number was obtained between trial-types for each individual. Stimulus-locked ERP averages were computed to: (1) stop-signals on trials where the response was successfully stopped (successful stop; SS), (2) stop-signals on trials where the response was not stopped (failed stop; FS), (3) ignore-signals on correct trials with RTs corresponding to the successful stop portion of the RT distribution (slow IG; IGs), and (4) ignore-signals on correct trials with RTs corresponding to the failed stop portion of the RT distribution

(fast IG; IGf). The rationale for separating ignore-signal trials into fast and slow RT averages is that successful stop trials consist of slower RTs, while failed stop trials consist of faster RTs (Logan, 1994). Response-locked ERP averages were computed to: (1) the overt response on failed stop trials, and (2) the overt response on correct ignore-signal trials across all RTs.

Due to the small magnitude of the component, N2 in the stimulus-locked ERPs was quantified as the mean amplitude in the 200 to 250 ms latency range, where the N2 was most consistently observed. The P3 component was quantified as the most positive peak in the 250 to 500 ms latency range (peak latency locked at Cz). For the response-locked ERPs, Ne was quantified as the most negative peak in the latency range of 0 to 150 ms following the overt button-press response (locked to Fz), and Pe as the most positive peak in the latency range of 250 to 350 ms (locked at Pz). Peak amplitudes were quantified within a predetermined latency window, relative to either the 100 ms pre-stimulus or pre-response period, by means of an automatic peak-picking program using Scan software (Neuroscan, v4.2). Quantified components were subsequently manually inspected.

Multivariate ANOVAs were used to analyse ERP amplitudes at the midline sites (Fz, Cz and Pz).<sup>3</sup> Within-subject factors included “Sagittal” (Fz vs. Pz, and Cz vs. the mean of Fz and Pz) and “Trial” (see below for description of contrasts), while the between-subject factor was “Group” (fast versus slow). The analyses for component peak latency excluded site contrasts. For stimulus-locked ERPs, the within-subject factor “Trial” included a comparison of successful stop trials with corresponding (slow)

ignore-signal trials and failed stop trials with corresponding (fast) ignore-signal trials.<sup>26</sup> A separate MANOVA was performed for response-locked ERPs, comparing failed stop trials with ignore-signal trials. Finally, MANOVAs were used to compare stop-signal locked components with response-locked components. As all contrasts were planned and there were no more of them than the degrees of freedom for effect, no Bonferroni-type adjustment to  $\alpha$  was necessary (Tabachnick & Fidell, 1989). Also, the single degree of freedom contrasts are not affected by violations of symmetry assumptions common in repeated measures analyses, and thus do not require Greenhouse-Geisser type corrections. In order to interpret scalp distributions within Trial and Group, the data were normalised with the vector scaling method, using the square root of the average of squared across-subjects mean amplitude (McCarthy & Wood, 1985), and only topographic interactions that remained significant after normalisation are reported. Unless otherwise indicated, degrees of freedom for all statistical effects reported are (1, 40).

## 6.4 Results

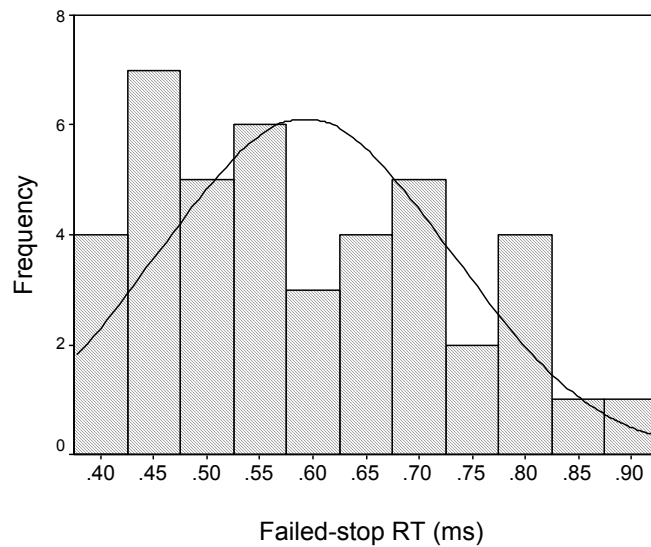
### 6.4.1 Performance Measures

Figure 6.1 displays the distribution of FSRTs across the whole sample. While 450 ms, followed by 550 ms, are the most frequent RTs in the distribution, this is followed by an equal proportion of RTs in the 500 and 700 ms ranges. This bi-modal distribution suggests that there were many subjects in the pool that tended to prolong responding to the primary task, and thereby, justifies the division of the sample into two

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<sup>26</sup> Orthogonal contrasts also compared the mean of successful-stop trials and slow ignore-signal trials with the mean of failed-stop trials and fast ignore-signal trials. However, effects involving this contrast were not reported as the comparison was not relevant to the conceptual issues examined in this thesis.

performance groups. The sample was divided using a median-split based on FSRT (median 562 ms). The distribution of FSRT between groups was investigated and it was found that, in both groups, RTs approximated a normal, symmetric distribution with small skew (slow: 0.807 vs. fast: -0.087).



**Figure 6.1. The distribution of failed stop RTs in the subject pool. Note: (1) x-axis indicates the RTs in seconds, (2) y-axis indicates frequency of each RT**

As can be seen in Table 6.1, the fast group also showed shorter mean RT to go stimuli for no-signal ( $F = 49.2, p < .001$ ), ignore-signal ( $F = 38.5, p < .001$ ) and failed stop trials ( $F = 87.7, p < .001$ ), relative to the slow group. However, there were no differences found between groups in the likelihood of committing an error of omission ( $F = 1.9, p = .180$ ) or choice ( $F < 1$ ). Furthermore, the accuracy of responding for ignore-signal trials was high in both groups and did not differ significantly ( $F < 1$ ). With respect to the stopping performance, average inhibition probability was reduced ( $F = 13.0, p = .001$ ) in the fast compared to the slow group, while neither the slope of the inhibition function ( $F < 1$ ) or SSRT ( $F < 1$ ) differed between groups.



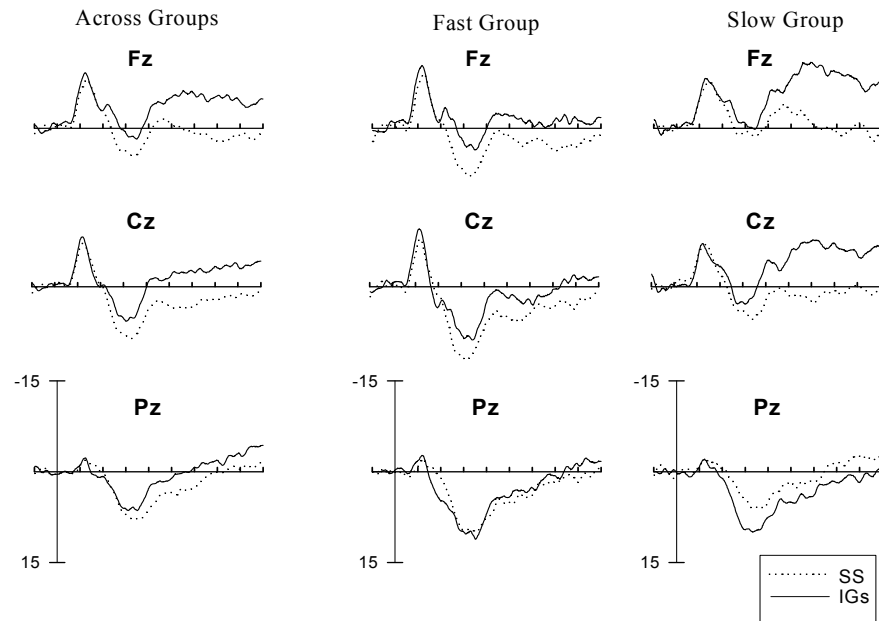
**Table 6.1. A summary of the means and standard deviations (in brackets) for performance measures in the fast and slow groups.**

	Fast	Slow
<b>MRT to go stimuli (ms)</b>		
<b>No-signal</b>	494.7 (54.3)	694.8 (119.4)
<b>Ignore-signal</b>	591.2 (77.4)	837.2 (164.9)
<b>Failed stop</b>	477.8 (52.2)	720.2 (107.0)
<b>SSRT</b>	232.3 (70.2)	234.6 (94.6)
<b>Probability (%)</b>		
<b>Omission errors</b>	2.6 (4.3)	5.4 (8.2)
<b>Choice errors</b>	1.4 (1.9)	1.1 (1.5)
<b>Ignore-signal Accuracy</b>	93.1 (10.6)	93.1 (5.9)
<b>Inhibition</b>	43.7 (16.5)	60.9 (14.7)
<b>Inhibition Function Slope</b>	-0.13 (.10)	-0.14 (.11)

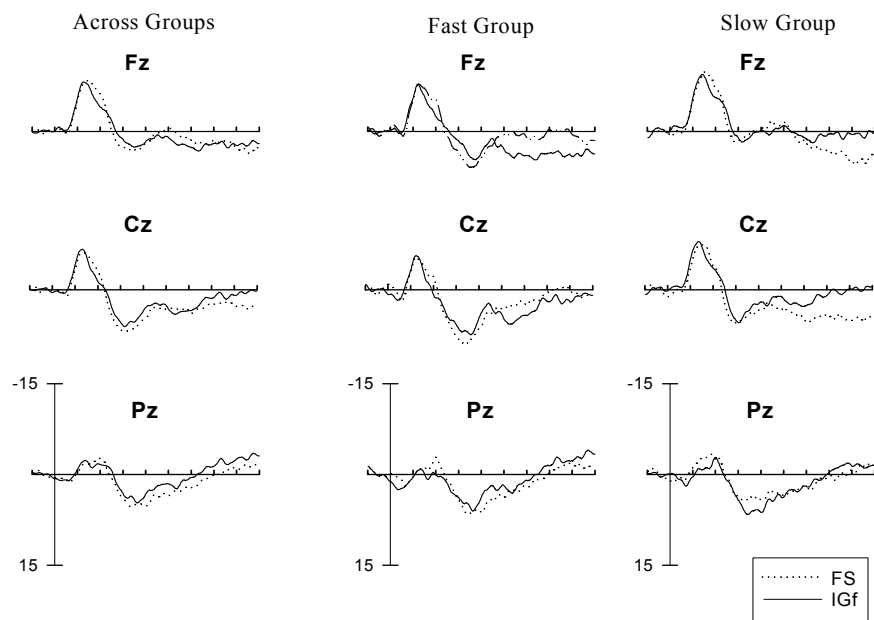
#### 6.4.2 Stimulus-locked ERP Components

Figures. 6.2 and 6.3 depict the average ERPs for successful stop compared to corresponding (slow) ignore-signal trials and failed stop compared to corresponding (fast) ignore-signal trials, respectively, plotted across groups (left panels), and between fast (middle panels) and slow groups (right panels). Figure 6.4 shows the topographic distribution of amplitude for each stimulus-locked component, for each trial-type and group separately.

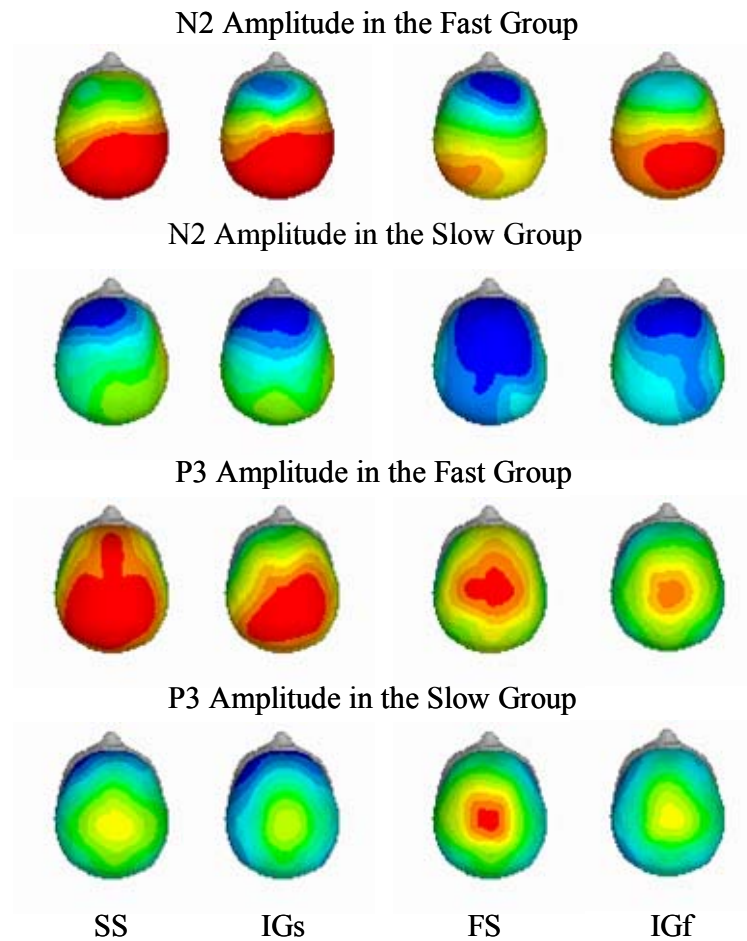
Across Trial and Group, N2 had a fronto-central maximum ( $Fz > Pz$ ,  $F = 60.0$ ,  $p < .001$ ;  $Cz > Fz/Pz$ ,  $F = 7.1$ ,  $p < .05$ ), while P3 showed a centro-parietal maximum ( $Fz < Pz$ ,  $F = 5.2$ ,  $p < .05$ ;  $Cz > Fz/Pz$ ,  $F = 126.9$ ,  $p < .001$ ).



**Figure 6.2.** Grand average ERP waveforms for successful stop (SS) and corresponding ignore-signal (IGs) trials across group (left panel), and within the fast (middle panel) and slow (right panel) groups. Notes: for this and the following figure, (1) x-axis ticks = 100 ms, (2) stimulus onset is indicated by vertical scale bar, (3) y-axis =  $\pm 15 \mu\text{V}$  (shown at Pz), (4) negative-going amplitude is up.



**Figure 6.3.** Grand average ERP waveforms for failed stop (FS) and corresponding ignore-signal (IGs) trials across group (left panel), and within the fast (middle panel) and slow (right panel) groups.



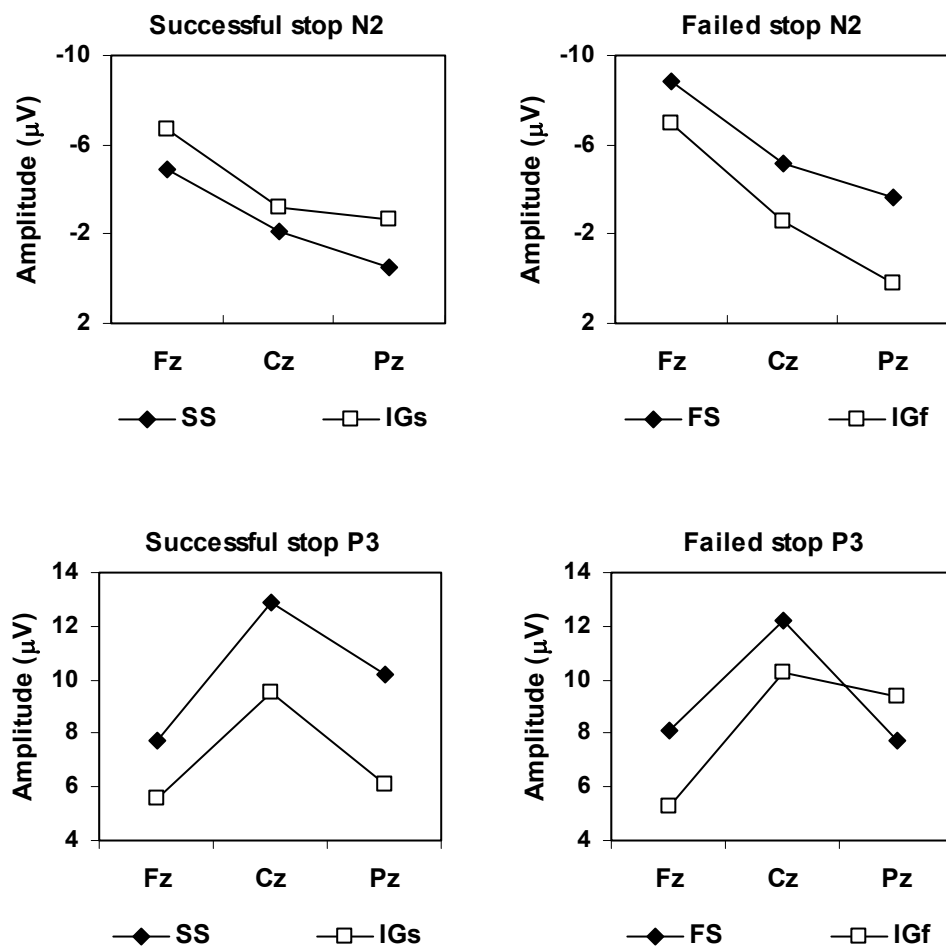
**Figure 6.4.** Topographic maps of the distribution of amplitude for each ERP component in the fast and slow groups for successful stop trials (SS), failed stop trials (FS), and ignore-signal trials corresponding to the successful (IGs) and failed stop (IGf) parts of the RT distribution. Notes: (1) N2 amplitude ranges from -7 to 0  $\mu\text{V}$ , (2) P3 amplitude ranges from 0 to 12  $\mu\text{V}$ .

#### 6.4.2.1 Successful and Failed Stop Effects

No effects remained significant after normalisation for N2 amplitude between successful stop and corresponding ignore-signal trials (see Figure 6.5, upper/left panel). In contrast, N2 amplitude was larger for failed stop than the corresponding ignore-signal trials across the midline ( $F = 5.4$   $p < .05$ ), with this effect showing a tendency to be largest in the parietal region ( $F = 3.5$ ,  $p = .068$ , see Figure 6.5, upper/right panel).

P3 amplitude was larger for successful stop compared to corresponding ignore-signal trials across the midline ( $F = 5.3$ ,  $p < .05$ ; see Figure 6.5, lower/left panel).

Between failed stop and corresponding ignore-signal trials, although failed stop P3 showed relatively equal amplitude across the frontal and parietal regions, ignore-signal trials showed greater amplitude in the parietal region ( $F = 6.3, p < .05, n^2 = .137$ ; see Fig. 3, lower/right panel). With respect to latency, P3 peaked later for failed stop compared to ignore-signal trials ( $F = 4.9, p < .05$ ).

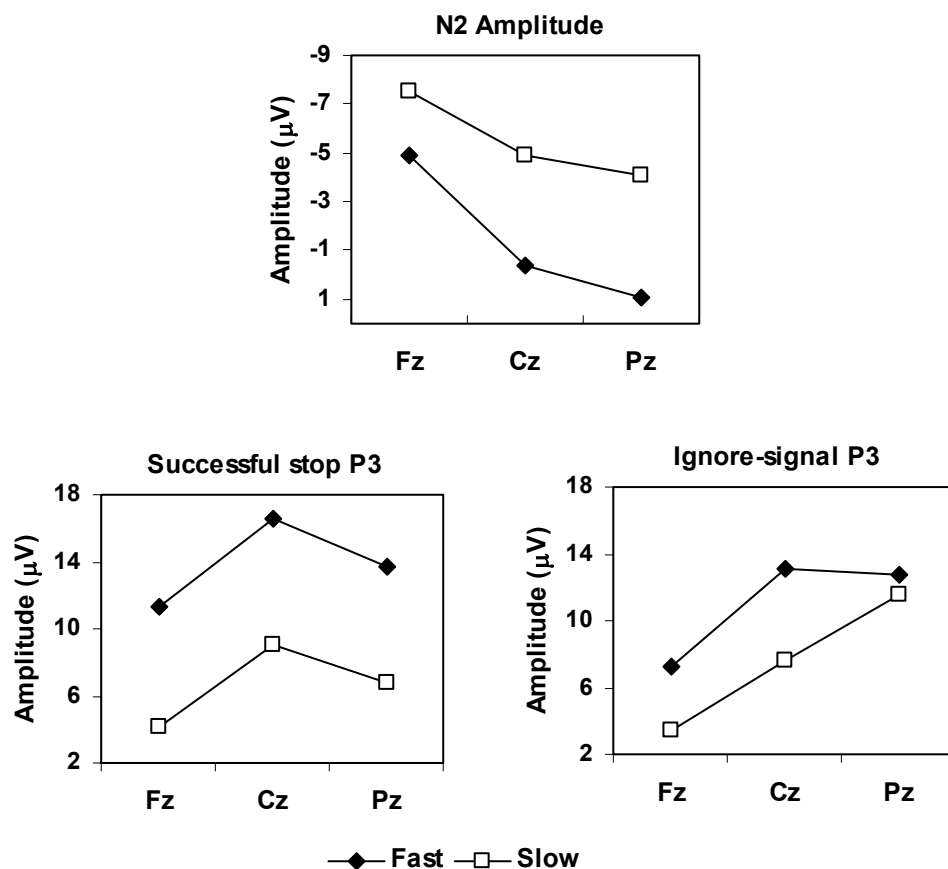


**Figure 6.5.** Trial effects for N2 amplitude (upper panel) and P3 amplitude (lower panel) for successful stop (SS; left panel) and failed stop (FS; right panel) trials versus corresponding ignore-signal trials (IGs and IGf), across Group. Note: for this and subsequent plots, the y-axis shows larger amplitudes at the top of the scale depending on the polarity of the component.

#### 6.4.2.2 Group Effects

N2 amplitude was larger in the slow compared to fast group across the midline sites ( $F = 10.8, p < .01$ ; see Figure 6.6, top panel), and the group difference did not differ between trials.

P3 amplitude was larger in the fast compared to slow group across the scalp ( $F = 6.1, p < .05$ ). A tendency towards an interaction with Trial ( $F = 3.4, p = .073, \eta^2 = .078$ ) spurred subsidiary analyses, which showed that the group difference was significant for successful stop trials ( $F = 10.4, p < .01$ ; see Figure 6.6, left panel) but not corresponding ignore-signal trials ( $F < 1$ ; see Figure 6.6, right panel). No between-group differences were found for failed stop and ignore-signal trials. There were no Group effects on peak latency.

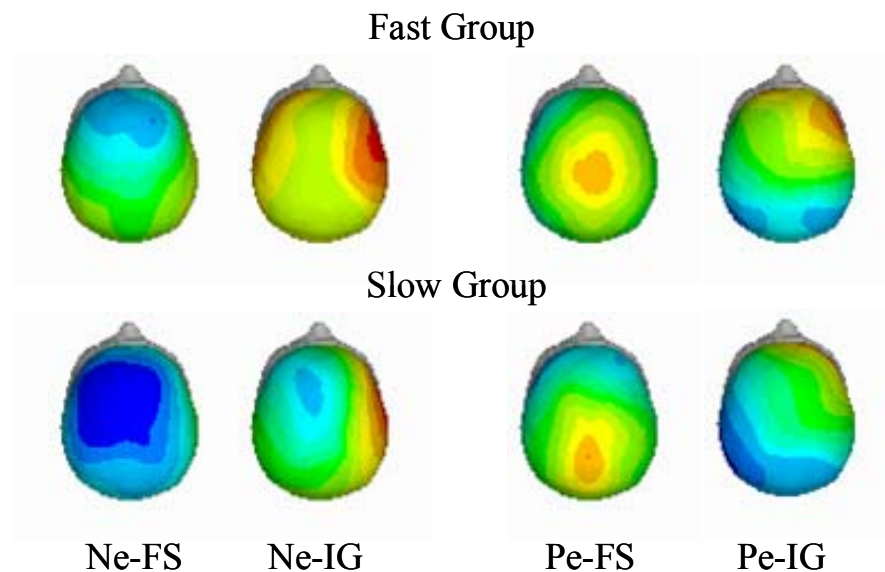


**Figure 6.6.** Amplitude at the midline sites between fast and slow groups for N2 (across Trials, top panel) and for P3, plotted separately for successful stop (left panel) and ignore-signal (right panel) trials.

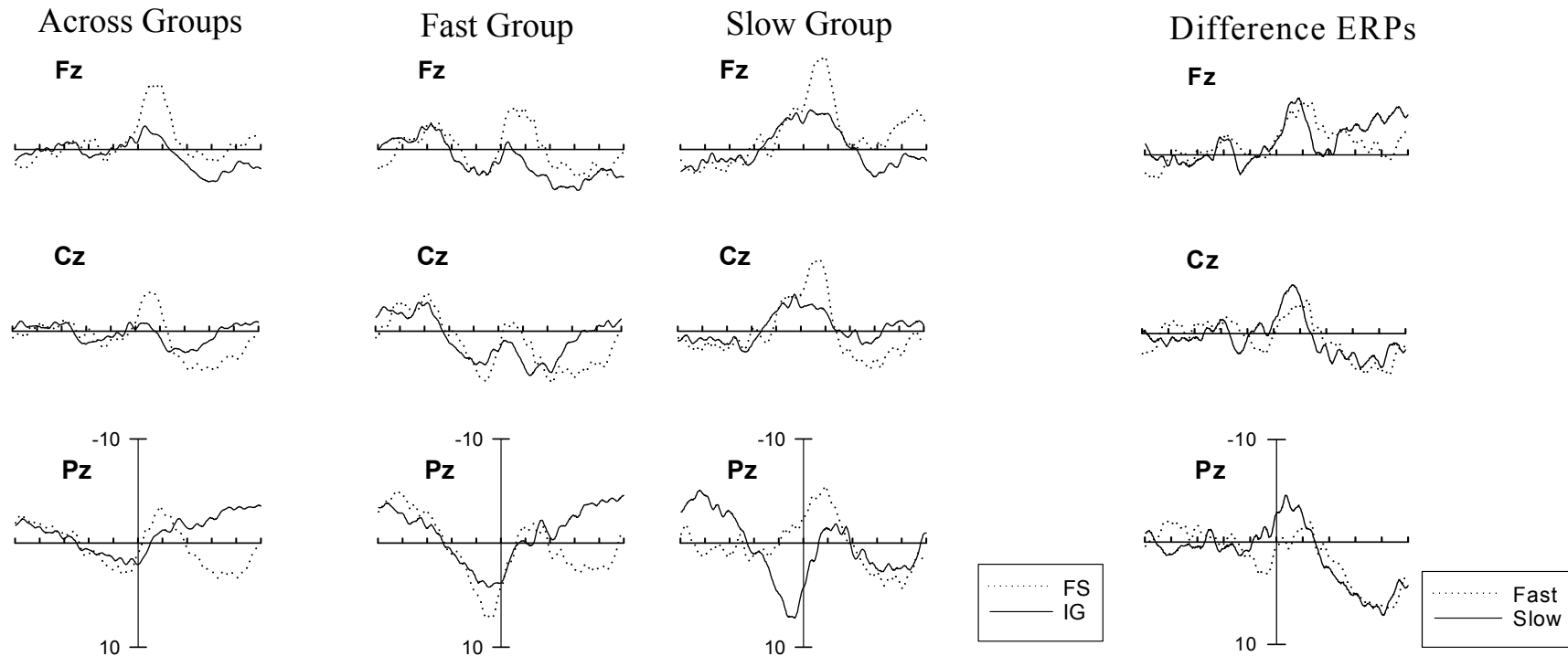
### 6.4.3 Response-locked ERP Components

Figure 6.7 shows the topographic distribution of amplitude for each response-locked component for each trial-type and group separately. Figure 6.8 displays the ERP waveforms for failed stop and ignore-signal trials plotted across groups (1<sup>st</sup> panel), and within the fast (2<sup>nd</sup> panel) and slow (3<sup>rd</sup> panel) groups. Figure 6.8 (4<sup>th</sup> panel) depicts the difference waveforms for failed stop minus ignore-signal trials between fast and slow groups.

Across Trial and Group, frontal maximas were found for Ne ( $F = 17.6, p < .001$ ) and Pe amplitude ( $F = 8.8, p < .01$ ).



**Figure 6.7.** Topographic maps of the distribution of amplitude for each response-locked ERP component in the fast and slow groups for failed stop (FS) and ignore-signal (IG) trials. Notes: (1) Ne amplitude ranged from -9 to 2  $\mu\text{V}$ , and (2) Pe amplitude ranged from -2 to 9  $\mu\text{V}$ .

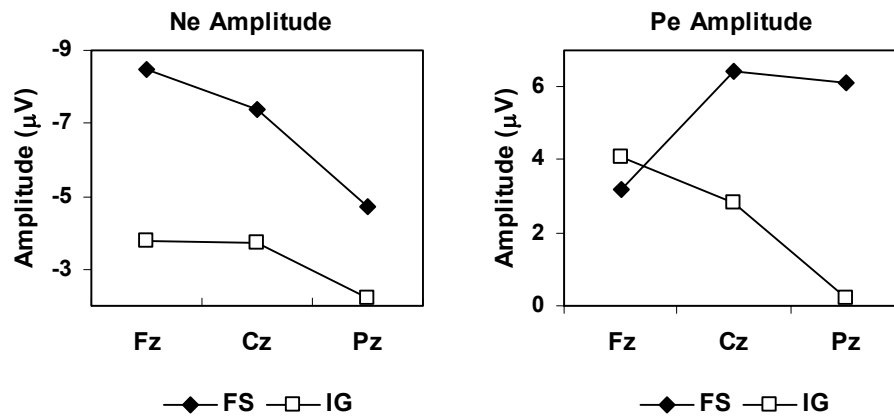


**Figure 6.8.** Grand average response-locked ERP waveforms for failed stop and ignore-signal trials: (a) across groups (1st panel), (b) within the fast group (2nd panel), (c) with the slow (3rd panel) group, and (d) the average difference ERP waveforms (failed stop minus ignore-signal) in the fast and slow groups (4<sup>th</sup> panel). Notes: (1) x-axis ticks = 100 ms, (2) response onset is indicated by vertical scale bar, (3) y-axis =  $\pm 10 \mu\text{V}$  (shown at Pz), (4) negative-going amplitude is up.

#### 6.4.3.1 Trial Effects

Ne amplitude was larger for failed stop compared to ignore-signal trials ( $F = 25.4, p < .001$ ), and this difference was largest in the frontal region ( $F = 4.8, p < .05$ ; see Figure 6.9, left panel).

Pe was larger for failed stop than ignore-signal trials across the midline ( $F = 6.1, p < .05$ ), and this difference was largest in the centro-parietal region ( $Pz > Fz, F = 37.6, p < .001$ ;  $Cz > Fz/Pz, F = 6.8, p < .05$ ; see Figure 6.9, right panel).

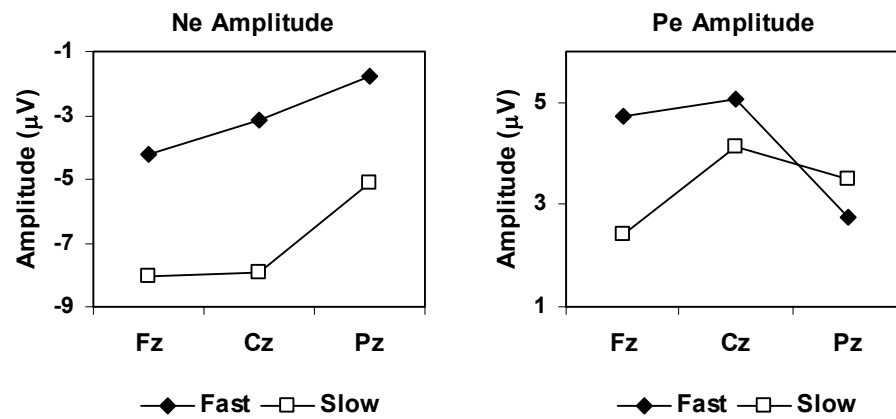


**Figure 6.9.** Amplitude at the midline sites, across Group, comparing failed stop (FS) and ignore-signal (IG) trials for the Ne (left panel) and Pe (right panel) components.

#### 6.4.3.2 Group Effects

Ne amplitude was larger in the slow than fast group across the midline ( $F = 8.7, p < .01$ ; see Figure 6.10, left panel). The fast group showed an  $Fz > Pz$  effect for Pe, with the converse effect found in slow subjects ( $F = 5.2, p < .05$ ; see Figure 6.10, right panel).

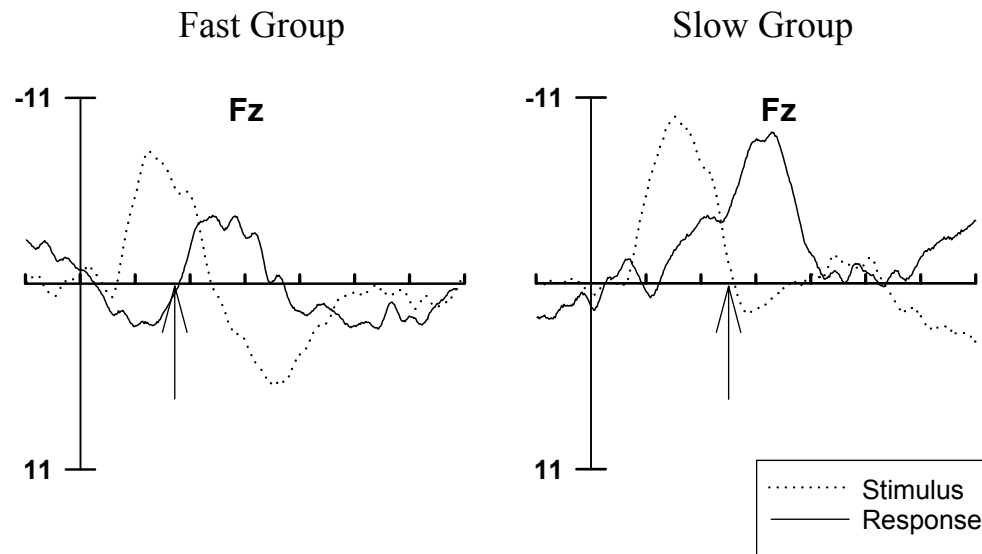




**Figure 6.10.** Amplitude at the midline sites, across Trial, comparing fast and slow RT groups for the Ne (left panel) and Pe (right panel) components.

#### 6.4.4 The Relationship Between Stimulus- and Response-locked ERPs

Figure 6.11 compares the stimulus- and response-locked ERP waveforms for failed stop trials for the fast and slow RT groups at Fz. As is evident in the figure, response-locked Ne appears to overlap the stimulus-locked N2 latency range in both groups, indicating that failed stop N2 may reflect an aggregate of stop-signal and error-related response processing (Ne). However, even more importantly, this suggests that reduced P3 amplitude on failed compared to successful stop trials may not reflect an inhibitory effect, but rather, may be due to the Ne component overlapping the failed stop P3.



**Figure 6.11.** Stimulus-locked (thin line) and response-locked (thick line) ERP waveforms for failed stop trials at Fz in the fast and slow RT groups. Notes: (1) x-axis ticks = 100 ms, (2) response onset is indicated by vertical scale bar, (3) y-axis =  $\pm 11 \mu\text{V}$ , (4) negative-going amplitude is up.

#### 6.4.4.1 Stop N2 and Ne

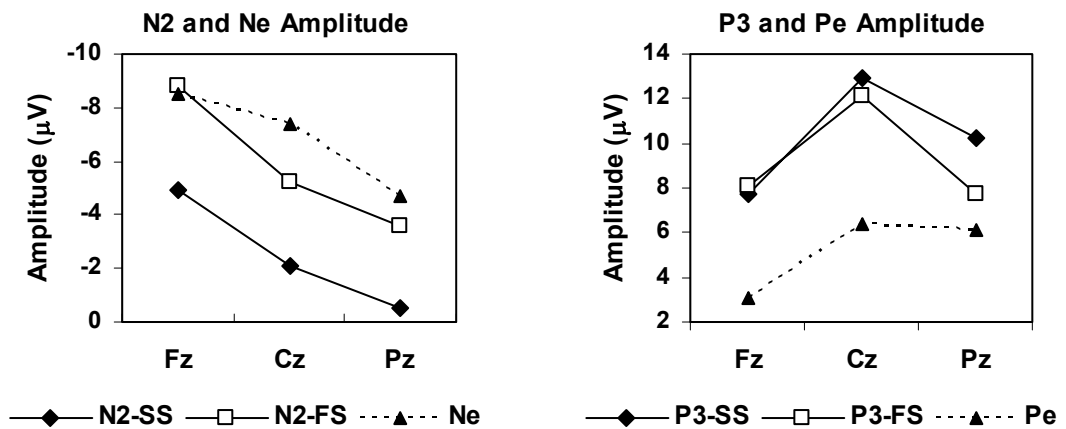
Amplitude was larger for Ne compared to successful stop N2 across the midline ( $F = 14.3, p < .01$ ), with this effect largest in the central region ( $F = 9.7, p < .01$ ; see Figure 6.12, left panel), and occurring largely in the slow than fast group ( $F = 3.9, p = .055$ ). Table 6.2 shows the Pearson's correlations values for each comparison between stimulus-locked N2 and response-locked Ne. Correlations revealed a significant positive relationship between successful stop N2 and Ne at Cz only, while correlations approached significance at Fz and Pz.

Ne showed a Cz > Fz/Pz effect that was reduced for failed stop N2 across groups ( $F = 5.9, p < .05$ ; see Figure 6.12, left panel). Correlations showed positive relationships between failed stop N2 and Ne at all midline sites (see Table 6.2).

**Table 6.2. Pearson's correlations at the midline sites for the response-locked Ne on failed stop-signal trials with the stop-signal locked N2 on successful stop (SS) and failed stop (FS) trials.**

Ne	N2-SS			N2-FS		
	Fz	Cz	Pz	Fz	Cz	Pz
Fz	0.258a	0.069	0.190	0.362*	0.186	0.312*
Cz	0.359*	0.335*	0.314*	0.466**	0.521**	0.555**
Pz	0.246a	0.197	0.265a	0.245a	0.324*	0.482**

Notes: \*\*Correlation is significant at the 0.01 level (2-tailed); \*Correlation is significant at the 0.05 level (2-tailed); a = approached significance at  $p < .10$ .



**Figure 6.12. A comparison of amplitude for stimulus-locked successful (SS) and failed stop trials (FS) for N2 with the response-locked Ne (left panel) and for P3 with Pe (right panel).**

#### 6.4.4.2 Stop P3 and Pe

Amplitude was larger for successful stop P3 compared to Pe across the midline ( $F = 13.0$ ,  $p < .01$ ), with this effect largest in the central region ( $F = 8.7$ ,  $p < .01$ ; see Figure 6.12, right panel), and greater in the fast than slow group ( $F = 5.3$ ,  $p < .05$ ). Table 6.3 shows the Pearson's correlations values for each comparison between stimulus-locked P3 and response-locked Pe. However, successful stop P3 did not correlate with Pe at any midline site.

Amplitude was larger for failed stop P3 compared to Pe across the midline ( $F = 15.6$ ,  $p < .001$ ), and this difference was largest in the centro-parietal region (Fz vs. Pz,  $F$

= 6.8,  $p < .05$ ;  $Cz > Fz/Pz$ ,  $F = 26.2$ ,  $p < .001$ ; see Figure 6.12, right panel). Failed stop P3 correlated positively with Pe at all midline sites (see Table 6.3).

**Table 6.3. Pearson's correlations at the midline sites for the response-locked Ne on failed stop-signal trials with the stop-signal locked P3 on successful stop (SS) and failed stop (FS) trials.**

	P3-SS			P3-FS		
Pe	Fz	Cz	Pz	Fz	Cz	Pz
Fz	0.066	0.142	0.157	0.581**	0.502**	0.399*
Cz	0.041	0.050	-0.017	0.580**	0.636**	0.474**
Pz	-0.048	-0.022	-0.084	0.369*	0.457**	0.440**

Notes: \*\*Correlation is significant at the 0.01 level (2-tailed); \*Correlation is significant at the 0.05 level (2-tailed); a = approached significance at  $p < .10$ .

## 6.5 Discussion

The present study aimed to further investigate the functional significance of the N2 and P3 components in the stop-signal task, through a comparison of stop-signal ERPs with task-irrelevant ignore-signal ERPs in fast and slow RT groups, and in relation to response-locked Ne and Pe.

### 6.5.1 Performance

The subject pool was divided into two groups using a median split of failed stop RTs to obtain fast and slow RT groups. As faster responses are more difficult to inhibit than slower responses, it was hypothesised that the fast group would require faster or greater inhibitory activation to successfully stop a response. Performance findings showed that the fast group responded faster across all response trials, showed a reduced likelihood of omitting a response, and a reduced inhibition probability, relative to the slow group. The groups, however, did not differ on SSRT, the slope of the inhibition function or primary task accuracy. These findings support the contention that subjects

who place a greater emphasis on fast responding in the primary task find it more difficult to inhibit their responses, with more responses escaping the inhibition process. In contrast, subjects who adopt a slower response style in relation to the primary task, do so in order to increase the likelihood of a successful inhibition, but as a result, show an increase in primary task RT. Thus, two response style groups were established in the present study, divided with a median split of failed stop RTs. It should be noted that the lack of a between-group difference for SSRT is in contrast to the notion that subjects who adopt a slower response style display faster SSRTs (de Jong et al., 1990; Logan, 1994), but is in line with the executive-control theory which states that the characteristics of the response process do not affect the latency of the inhibitory response because the inhibition process is a higher-order function that works on the lower-order subsidiary response processes (Band & van Boxtel, 1999; Logan & Cowan, 1984). These findings suggest that, in order to successfully stop a response, the fast group had to evoke a *greater* magnitude of, rather than *faster*, inhibitory activation, relative to the slow group.

### 6.5.2 *The Successful Stop N2*

The comparison of stop-signal and ignore-signal trials was aimed at isolating processing specifically related to the success and failure of inhibition. Typically, successful stop trials are examined in relation to failed stop trials, however, this comparison may confound interpretation as both trial-types are task-relevant and appear to activate quite different neural networks that probably reflect a distinct set of sensory, cognitive and motor processes (Dimoska et al., 2003; Kok et al., 2004; Ramautar et al., 2004; Rubia et al., 2003). In the present study, it was predicted that successful stop trials would be characterised by greater amplitude of the component reflecting

inhibitory activation, relative to ignore-signal trials. However, successful stop N2 did not differ from ignore-signal trials. Furthermore, a comparison of fast and slow RT groups revealed that N2 was enhanced in the slow compared to fast group, across all trial-types. These findings are not compatible with the notion that N2 amplitude reflects the stop-signal inhibition process *per se*, as stopping an ongoing response was more difficult in the fast compared to slow group, and would therefore, require greater inhibitory activation.

However, as inhibition probability was greater in the slow than fast group, this suggests that N2 may be related to inhibition in some other form. Larger N2 amplitude and greater inhibition probability in the slow compared to fast group is in line with Falkenstein et al. (1999), who found a larger nogo N2 and slower MRT in a group of *good* compared to *poor* inhibitors, divided using the frequency of failed stop trials. These findings suggest that N2 may play a general role in controlling response execution, as opposed to reflecting the inhibition process itself. This is further supported by the fact that N2 on inhibition trials has been linked with the prefrontal cortex (Kiefer et al., 1998; Mathalon et al., 2003; Rubia et al., 2003; Swainson et al., 2003; but see van Veen & Carter, 2002 for evidence that ACC may also contribute to the N2), a region found to play a primary role in executive control decisions relating to the selection (Rowe et al., 2000; Rubia et al., 2003) or switching of responses (Garavan et al., 2000). Therefore, the N2 may be generally related to the modulation of response processing, whereby the inhibitory response is deliberately selected during the early stages of response preparation and selection in the PFC (Kok, 1986; Kopp, 1996; Swainson et al., 2003). If the response has already been selected by the time the instruction to inhibit is identified, such as with fast responses in the stop-signal task, this

process may be “by-passed” because there is no time to deliberately select the inhibitory response. Rather, responses then have to be stopped using an urgent inhibitory brake.

An alternative hypothesis is that N2 for successful stop trials reflects an evaluative process that detects the occurrence of conflict between the go and inhibitory responses, and that on failed stop trials, this process manifests in the response-locked Ne component (Nieuwenhuis et al., 2003; Van Veen & Carter, 2002). On successful stop trials, the conflict is small because the inhibition response overrides the go response before it is executed, however, on failed stop trials, conflict is large and occurs after the onset of the overt response, when both the go and inhibition responses are maximally active. Therefore, according to this hypothesis, as the successful stop N2 and response-locked Ne are thought to be manifestations of the same response-conflict process located in the ACC (Nieuwenhuis et al., 2003), they should display similar topographic distributions on the scalp surface. However, a larger central maximal was found for the Ne compared to successful stop N2, while correlations revealed a significant positive relationship at Cz only, with the correlations at Fz and Pz approaching significance. These findings are in contrast to the response-conflict hypothesis, and are consistent with some studies showing differences in the distribution of N2 and Ne (Falkenstein et al., 1999; Mathalon et al., 2003), but not with others (Donkers & van Boxtel, 2004; Nieuwenhuis et al., 2003; Van Veen & Carter, 2002). Using ERPs and fMRI, Mathalon et al. (2003) showed that the N2 reflected activation of both the dorsolateral PFC and caudal ACC, suggesting a role in both conflict and control (Carter et al., 1998). Therefore, a different distribution of N2 on the scalp surface may not necessarily discount a role in response conflict. Nevertheless, the present findings did not unequivocally support the response-conflict theory for

successful stop N2, and suggest that the component may be a better index of deliberate response selection (Mathalon et al., 2003; Pailing et al., 2002; Swainson et al., 2003).

### 6.5.3 *The Successful Stop P3*

A common finding is larger P3 amplitude for successful than failed stop trials (Dimoska et al., 2003; Overtom et al., 2002). In the present study, relative to ignore-signals, P3 was enhanced for successful, but not failed, stop trials. This finding supports the P3's relation to inhibitory processing and to the success of inhibition (Kok et al., 2004; Ramautar et al., 2004). Furthermore, P3 was larger for the fast compared to slow group, with this effect occurring for successful stop trials. This is in line with the notion that fast responders require urgent inhibitory control with greater phasic inhibitory activation to successfully inhibit a response, relative to slow responders. Therefore, the successful stop P3 is interpreted in line with this process. Kok et al. (2004) found that the successful stop P3 had a source located near the motor or pre-motor cortex, which they interpreted as reflecting a stop-signal inhibition process in this region. Some researchers have suggested that the P3 appears to peak too late to reflect the action of the inhibition process (Naito & Matsumura, 1996). Although the successful stop P3 in the present study peaked 70 ms after the estimated SSRT, this does not exclude the P3's relation to inhibition. It is suggested that the successful stop P3 may reflect the "site" or "manifestation" of inhibition working on central response activation in or near the primary motor cortex, rather than the inhibition process itself (Kok et al., 2004; Ramautar et al., 2004). In this context, P3 amplitude was larger in the fast group because faster responses were more often stopped in this region, that is, the last cortical point of stopping before motor output moves to the brainstem and



subsequently to the periphery (Band & van Boxtel, 1999). In contrast, slow responses are more likely to be stopped before they reach the primary motor cortex.

Kok (1986) suggested that enhanced P3 amplitude on successful compared to failed stop trials may be due to movement-related negativity found on failed stop trials, rather than reflecting inhibition. In the present study, it is feasible that motor-related negativity on ignore-signal trials reduced P3 amplitude, but if this was the case, fast subjects should have shown reduced P3 amplitude, relative to slow subjects, as motor-related negativity is greater preceding faster responses. Previous studies have shown a greater incidence of motor-related negativity in the form of the readiness potential (RP) and contingent negative variation (CNV) for fast compared to slow responses (Band et al., 2003a). Therefore, the successful stop P3 effect may be attributed to inhibitory activation, rather than an absence of motor-related negativity.

With respect to the relationship between successful stop P3 and response-locked Pe, the former component had a more central distribution than the frontal Pe, while correlations were not significant at any site. While the P3 and Pe components were previously found to be related in the go/nogo task (Davies, Segalowitz, Dywan, & Pailing, 2001), the present findings suggest that these two components reflect distinct processes.

#### *6.5.4 Response-locked ERP Components*

The response-locked Ne and Pe components displayed larger amplitude for failed stop compared to ignore-signal trials. This corresponds with the notion that Ne and Pe are associated with “erroneous” response processing (Gehring, 1993; Nieuwenhuis et al., 2001), and shows that these components are present for failed stop trials. Traditionally, the Ne has been associated with the detection of an error, while Pe

has been associated with the evaluation of, or affective processing related to, an error (Falkenstein et al., 2000; Nieuwenhuis et al., 2001). However, as outlined above, Ne may play a role in the detection of response conflict, rather than error.

It has been suggested that N2 and P3 on failed stop trials may be associated with the detection of the inability to stop a response on a stop-signal trial (Kok et al., 2004). Typically, failed stop N2 trials shows a central enhancement (Dimoska et al., 2003; Kok et al., 2004), relative to successful stop trials. An examination of failed stop N2 relative to the ignore-signal trials showed enhanced amplitude, particularly in the parietal region. This topographic difference suggests that the Ne component, which is large across the midline region (Van Veen & Carter, 2002), overlapped the failed stop N2 (Hajcak et al., 2003). Coles, Scheffers, and Holroyd (2001) suggest that stimulus-locked components could contaminate response-locked components due to fast response times, and vice versa. The comparison of stimulus and response-locked ERP waveforms for fast and slow RT groups revealed the Ne occurred closer to the stop-signal in the former group, resulting in greater component overlap (Davies et al., 2001), although component overlap was an issue for both groups due to the fast nature of responses on failed stop trials. Likewise, an examination of the stop-signal ERP waveforms in Figure 5 of van Boxtel et al. (2001, p 252) shows a bi-phasic negative component for failed stop trials (termed “respond”) that suggests the overlap of a response-related negativity. The comparison of failed stop N2 and Ne showed some differences in topographic distribution, but correlations were significant across all midline sites, suggesting that an increase in Ne amplitude was associated with an increase in failed stop N2. Furthermore, both the failed stop N2 and Ne showed larger amplitude for slow than fast subjects across the entire scalp. Thus, the failed stop N2 probably reflects an aggregate of stop-signal and response-related processing.

These findings indicate that component overlap was also an issue for the failed stop P3, as the Ne would have caused a reduction in P3 amplitude. Therefore, the typically found enhancement of P3 amplitude on successful compared to failed trials may not necessarily reflect differences in inhibitory activation, but rather, be due to error-related negativity on failed stop trials. This is an important finding because it clarifies why some researchers have found larger P3 amplitude for failed compared to successful trials instead. A comparison of failed stop P3 with Pe revealed that the latter component was associated with a greater parietal > frontal gradient, however, correlations revealed significant relationships at all midline sites and both components showed no global changes in amplitude or latency between the slow and fast groups' subjects. Therefore, the failed stop P3 may partially reflect Pe-related processing.

#### 6.5.5 *Limitations*

A limitation of this study was that inhibitory activation was examined in fast and slow RT groups, which were divided post-hoc. A stronger experimental design would be to directly manipulate response activation requirements or the bias towards/against responding as a method of varying the requirement for inhibitory activation. A second limitation was that subjects used the dominant hand to respond and, therefore, the LRP, an electrophysiological index of response-side specific preparation, could not be computed to examine the relative preparation of responses between fast and slow RT groups.

### 6.5.6 Summary

The findings in the present study indicated that: (a) auditory stop N2 does not reflect the urgent inhibitory action typically evoked for stopping ongoing responses in the stop-signal task, but rather, may reflect a prefrontal executive response-modulation process that *selects* the inhibitory response whilst response processing is in preparational stages, (b) successful stop N2 and response-locked Ne reflect the manifestation of different underlying sources, in contrast to the response-conflict theory, (c) successful stop P3 may reflect the urgent inhibitory action of stopping a response at the last cortical site of inhibition, in or near the primary motor cortex, (d) ERPs on failed stop trials are overlapped by the response-locked, error-related Ne and Pe, and (e) the typically found enhancement of P3 amplitude on successful compared to failed trials probably does not reflect inhibitory requirements, but is a by-product of enhanced Ne on failed stop trials. Together, these findings present an intriguing functional dissociation of stop N2 and P3 in adults as a consequence of the response style and strategy adopted.

The findings presented here on the functional significance of the stop N2 and P3 components in adults suggest an intriguing dissociation, with the activation of distinct processes based on the relative requirements of the degree of inhibitory control. As outlined in the limitations section above (section 6.5.5), the degree of inhibitory activation was examined between groups created post-hoc. A direct manipulation of inhibitory requirements would provide a valuable insight into the distinction between deliberate response selection, as reflected in the N2 component, and an urgent inhibitory brake, as reflected in the P3 component. In response to this, Study IV (Chapter 7) examines the effect of manipulating stop-signal frequency, previously shown to induce a bias towards or against response activation (Logan & Burkell, 1986; Ramautar et al.,

2004), and therefore, directly affect inhibitory requirements. Therefore, the aim of the following study is dissociate the oddball effect from true inhibitory requirements.

## **7. Study IV - The effects of varying stop-signal probability on inhibitory and response activation processes**

### **7.1 Abstract**

The principal aim of the study was to examine the effect of varying stop-signal probability on inhibitory performance and ERPs. Thirty adult subjects completed two conditions of the selective stop-signal task where stop- and ignore-signal frequencies were varied (30 versus 70 %) within 60 % of primary task trials. As anticipated, presenting stop-signals rarely (30 % of auditory trials) was associated with reduced inhibition probability and enhanced LRP amplitude, suggesting a greater bias toward response processing that was more difficult to inhibit, relative to frequent stop-signals (70 % of auditory trials). SSRT remained unaffected by probability manipulations. Across conditions, all components showed enhanced amplitude for successful stop compared to ignore-signals trials, which was interpreted as reflecting the early exclusion of sensory input from further processing once the ignore-signal was identified as irrelevant. Between conditions, the N1/P3 complex was enhanced for rare compared to frequent auditory stimuli, while N2 amplitude showed the converse effect. However, probability effects did not differ between successful stop and ignore-signal trials, suggesting that modulations of component amplitudes with the probability of stop-signals did not reflect varying inhibitory requirements, but rather, oddball effects. Finally, a PCA revealed a probability main effect for the factor reflecting a slow-wave component, with no other factors differing between conditions, indicating that slow-wave activity may have partially accounted for enhanced N1/P3 amplitudes to rare stimuli.

## 7.2 Introduction

Responding in a dynamic environment requires a balance of go and inhibition processes. Decreasing stop-signal probability encourages a bias towards the go process and may be associated with impulsive behaviour such as fast and less accurate responding, as well as, a poorer ability to inhibit inappropriate responses. Conversely, increasing stop-signal probability may promote a slower and more accurate response style, accompanied by a greater control over response tendencies (Band et al., 2003a). The findings reviewed in section 1.7.3 support these notions. However, the latency of the inhibitory response appears to remain unaffected by stop-signal probability (Logan & Burkell, 1986; Logan et al., 1984; Ramautar et al., 2004).

With respect to ERPs, a review of the literature (section 3.6.3) shows that a decrease in stop-signal or nogo probability is associated with larger N2 and P3 amplitude (e.g. Ramautar et al., 2004; Eimer, 1993), and these effects have been interpreted as reflecting greater inhibitory activation to counteract the larger bias towards responding. However, the review also shows that increases in component amplitude with a decrease in stimulus probability may not be entirely attributable to increases in inhibitory requirements. N2 and P3 amplitudes show an inverse relationship with stimulus probability, regardless of response assigned to the stimulus (Banquet, 1981; Bruin & Wijers, 2002; Czigler et al., 1996). Therefore, ERP differences with stimulus probability may actually reflect “oddball effects”, whereby rare stimuli evoke greater cortical responses merely because they are novel within the prevailing stimulus context (Duncan-Johnson & Donchin, 1977). Nevertheless, the N2 enhanced amplitude for rare compared to frequent stimuli has been found to be larger for nogo than go stimuli, suggesting the presence of two components: one related to stimulus probability and other to response inhibition (Eimer, 1993; Nieuwenhuis et al.,

2003). Therefore, although modulations of N2 and P3 amplitude with stop-signal probability may be confounded by oddball effects, they may also reflect true inhibitory processing differences.

In Study III (Chapter 6), larger N2 amplitude for slow responders suggested that successful stop N2 may become enhanced when subjects have time to select the inhibitory response during response preparational stages, while fast responders showed a larger successful stop P3, reflecting urgent inhibitory control. In the present study, successful stop N2 may become enhanced when stop-signals are frequent because there is a bias towards inhibition, and subjects would have time to selectively choose the inhibitory response during response preparation, as opposed to having to stop an ongoing response. However, the above review suggests otherwise, with a decrease in the probability of nogo stimuli associated with an increase in N2 amplitude. This may reflect the large “oddball” response to rare stimuli subsuming other task-related effects. Nevertheless, if N2 reflects activation of a response selection process in the dorsolateral PFC, successful stop trials may show greater amplitude for frequent compared to rare stop-signals, while ignore-signal trials should show the typical converse effect. Furthermore, if P3 reflects urgent inhibitory control of central response activation at the last cortical site of inhibition, that is, the primary motor cortex (Kok et al., 2004), the enhancement for rare compared to frequent stimuli should be greater for successful stop than ignore-signal trials.

In the present study, to examine whether the experimental manipulation of the go and inhibition processes was achieved through the varying of stop-signal probability, processes related to response preparation were examined using LRP amplitude (Band et al., 2003a). The LRP provides an index of response-side specific motor preparation in the motor cortex, such that larger amplitude reflects greater preparation of a specific left



or right hand response. As presenting stop-signal less frequently is proposed to encourage a bias towards responding to the primary task, it was anticipated that LRP amplitude would be greater for rare compared to frequent stop-signals. Furthermore, the duration of perceptual and motor-related processes were estimated using the onset of the stimulus-locked LRP and the interval between the onset of the response-locked LRP and RT, respectively (Hsieh & Yen-Ting, 2003; Osman et al., 2003), although no specific predictions were made regarding these measures.

The primary aim of the present study was to determine whether probability differences for stop-signal ERPs reflect the greater recruitment of inhibitory processes or whether these effects are merely due to differences in stimulus probability. Previous studies varying nogo or stop-signal probability have not attempted to dissociate these two factors. This aim was achieved by examining the effect of varying the probability of the task-irrelevant ignore-signal, as well the stop-signal, in the selective stop-signal task. Specifically, it was hypothesised that (a) inhibitory activation would be greater for rare compared to frequent stop-signals, as reflected in a difference in P3 amplitude, and (b) that this difference would be greater for stop- compared to ignore-signal trials, thereby, ruling out oddball effects. Furthermore, it was hypothesised that N2 would show enhanced amplitude for frequent compared to rare stop-signals, suggesting a functional dissociation from the P3 component. With regards to the go process, it was hypothesised that rare stop-signals would encourage a faster, more impulsive response style, compared to frequent stop-signals, and that this would manifest as (a) fast RT to the primary task and reduced inhibition probability, and (b) greater response-side specific motor preparation for successful stop trials, as reflected in larger LRP amplitude.

### 7.3 Method

#### 7.3.1 Subjects

Thirty adults (10 males) aged 17 years 11 months to 31 years 8 months (mean age = 22.1 years, SD = 3.3 years) participated in this study. Subjects were included if they had never suffered an epileptic seizure, serious head injury, period of unconsciousness or any psychiatric condition. Each subject reported no problems with hearing and had normal or corrected-to-normal vision. Informed consent was obtained from all subjects after the testing equipment had been explained, with the option to withdraw without penalty.

#### 7.3.2 Stop-signal Task

Stop-signal task specifications are as for the selective stop-signal task in Study II (Chapter 5), except that the probability of the stop- and ignore-signals differed. Subjects completed two conditions, with order of presentation counter-balanced between subjects. In the *rare* condition, stop-signals were presented on 18% of trials (30 % of auditory trials), while ignore-signals were presented on 48% of trials (70 % of auditory trials), and in the *frequent* condition, this event probability was reversed. Digit II of the left and right hands were used to respond by pressing one of two buttons on a computer keyboard, which were marked with the words *apple* (Alt key) and *lion* (Ctrl key).

The stop-signal delay, was varied relative to each subject's mean Go MRT from the preceding block (Schachar & Logan, 1990b). It was observed in Study II (Chapter 5) that a delay of (MRT – 600) ms in a typical, non-clinical sample was surplus, therefore, delays in the present study were set at (MRT – 0) ms, (MRT – 100) ms,

(MRT – 200) ms, (MRT- 300) ms or (MRT – 400) ms. MRT was calculated using correct no-signal trials only. In the practice blocks, stop-signals were set to occur either 100 ms, 200 ms, 300 ms, 400 ms, or 500 ms after the onset of the go stimulus. Stop-signals could be presented either at or after go stimulus onset, but never before this point. If the MRT was less than 400 ms, stop-signals for the (MRT – 400) ms delay were set to occur at the onset of the go stimulus. The delay between go stimuli and ignore-signals was calculated in the same manner.

### 7.3.3 Procedure

Subjects began by completing an information sheet used to screen for stimulant use, handedness and history of health concerns. In the laboratory, each subject was familiarised with the testing equipment and procedure. After equipment fitting, subjects were seated in a sound-attenuated testing room where they completed the stop-signal task. In the first practice block (50 trials), subjects completed the primary task without any auditory tones, and were told to respond quickly and accurately to the presentation of go stimuli. In the second practice block (50 trials), the stop- and ignore-signals were introduced, with subjects told to respond quickly and accurately to the primary task, but to withhold that response if they heard the stop-signal (described as the higher-pitched tone) and to ignore the ignore-signal (described as the lower-pitched tone) and continue responding. Emphasis was placed on speed and accuracy for primary task performance, rather than successful stop.

After the two practice blocks, subjects completed three experimental blocks (150 trials) of each condition, with the presentation of conditions counter-balanced between subjects. In order to deter subjects from delaying their responses, subjects were told they should not wait for the tones, as they would be unable to inhibit their response on

every trial. It was explained that the onset of the stop- and ignore-signals was dependent upon their RT to the primary task, so that delaying responses would only delay the presentation of the tones on subsequent trials. Go MRT was displayed on the screen after each block, allowing subjects to rest briefly and to track their response speed, and also allowing the experimenter to monitor subjects for response-delaying strategies. In this instance, the experimenter emphasised the necessity for fast responding, and instructed the subject to attempt to obtain a shorter Go MRT in the next block.

#### 7.3.4 *Electrophysiological Recording*

All details for the recording of ERPs in this study are as outlined in Study I (Chapter 4). In brief, EEG was recorded from 17 sites of the International 10-20 system.

#### 7.3.5 *Data Analysis*

##### **7.3.5.1 Performance Measures**

All measures were as outlined in Study II (Chapter 5). Repeated measures multivariate ANOVAs were used to analyse all performance measures with Condition (*rare* 30 % stop-signal probability vs. *frequent* 70 % stop-signal probability) as a within-subjects factor. Analysis of the inhibition function included Delay as an additional within-subjects factor, comparing data at (MRT – 0) through to (MRT – 400) ms, using planned orthogonal polynomial contrasts.

### 7.3.5.2 Lateralised Readiness Potential

For the stimulus-locked LRP, ERPs were locked to the onset of the go stimulus, defined as 100 ms pre to 900 ms post-stimulus onset, and for the response-locked LRP, ERPs were defined as 500 ms pre to 500 ms post-response onset. All waveforms were filtered using a low-pass filter down 3 dB at 8.8 Hz (Ruchkin & Glaser, 1978). To compute the LRP, the waveforms measured at C4 were subtracted from the waveforms measured at C3 for left and right hand responses separately. Subsequently, the difference waveforms obtained for the left hand responses were subtracted from the corresponding waveforms obtained for right hand responses. In formula,  $LRP = \text{Right Hand (C3 - C4)} - \text{Left Hand (C3 - C4)}$ . This procedure results in negative-going waveforms of the activity contralateral to the side of the response, with lateralised activity unrelated to the side of the response cancelled out (Eimer & Schlaghecken, 1998). LRPs were derived separately in the rare and frequent conditions for successful stop trials,<sup>27</sup> correct ignore-signal trials and correct no-signal trials. The peak amplitude was determined in the latency window of 250 to 600 ms post go stimulus onset for the stimulus-locked LRP and -500 to 0 ms preceding response onset for the response-locked LRP.

LRP onset was scored using both a segmented regression procedure (Schwarzenau et al., 1998) and a criterion procedure (30 % of peak amplitude) (Osman & Moorer, 1993; see Appendix B for a comparison of procedures) in order to cross-check results. Each procedure was applied to each subject individually. Repeated measures multivariate ANOVAs were used to analyse all LRP measures with Trial (analysis 1 = ignore-signal trials vs. successful stop trials; analysis 2 = ignore-signal

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<sup>27</sup> As the outcome on successful stop trials is a no-response, LRPs for these trials may include some trials where the incorrect response was activated .

trials vs. no-signal trials), and Condition (*rare* 30 % stop-signal probability vs. *frequent* 70 % stop-signal probability) as within-subjects factors. In line with Miller et al. (1998), the present study reported the mean difference in LRP onsets between trial-types and conditions.

### 7.3.5.3 Event-related Potentials

ERPs time-locked to auditory tones were defined as 100 ms pre to 900 ms post-stimulus onset and were computed in the rare and frequent conditions for successful stop and ignore-signal trials (fast and slow RTs) separately (mean number of epochs = 34.5, SD = 15.7). The peak amplitude for each component was quantified within a predetermined latency window by means of an automatic peak-picking program, using Scan software (Neuroscan, v4.3), with the peak latency for each component fixed across all sites to the peak latency of the site of maximum amplitude (Pailing & Segalowitz, 2004; Picton et al., 2000). Stimulus-locked ERP components quantified included the N1 (70 – 160 ms, locked to Cz) and P3 (250 – 500 ms, locked to Cz), with peak amplitude measured relative to a 200 ms pre-stimulus baseline. The N2 was quantified as the mean amplitude in the 200 to 250 ms latency range. However, a PCA was performed using a covariance matrix and Varimax rotation to determine the component structure of activity in this latency range (see section 7.4.4 for details).

Repeated measures multivariate ANOVAs were used to analyse ERP amplitude with the following within-subject factors: Laterality [Left (F3, C3, P3); Midline (Fz, Cz, Pz); Right (F4, C4, P4)] and Sagittal [Frontal (F3, Fz, F4); Central (C3, Cz, C4); Parietal (P3, Pz, P4)] examining topography. Planned contrasts for examining ERP amplitude were as outlined in Study II (Chapter 5). Analyses for peak latency excluded site contrasts. To examine stimulus probability effects on successful stop ERPs, within-

subject factors included “Trial” (successful stop trials vs. corresponding ignore-signal trials) and “Condition” (30 % rare versus 70 % frequent). In order to interpret scalp distributions within Condition and Trial, the data were normalised (McCarthy & Wood, 1985), and only topographic interactions that remained significant after normalisation are reported. For brevity, only significant effects due to Trial or Condition, or an interaction of these variables with topography, have been reported. Unless otherwise indicated, degrees of freedom for all statistical effects reported are (1, 29).

## 7.4 Results

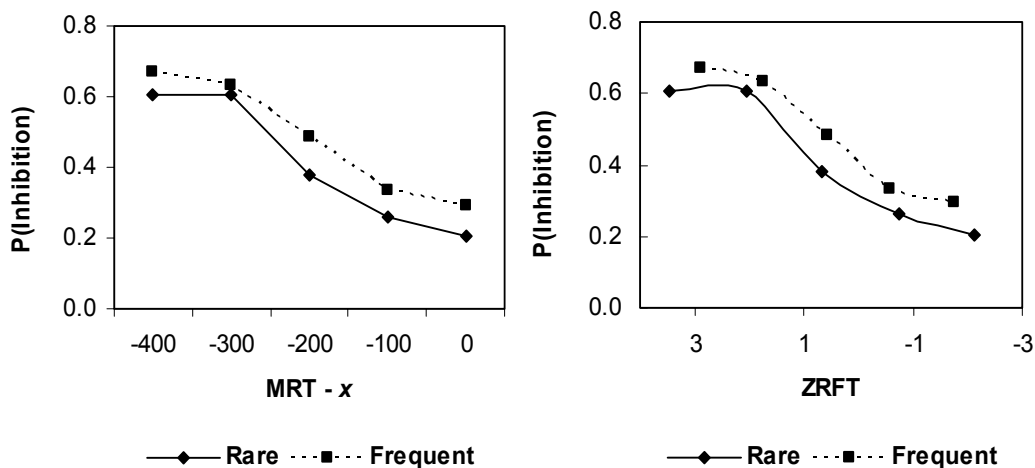
### 7.4.1 Performance Measures

Table 7.1 shows the means and standard deviations for all performance measures. SSRT did not differ between conditions ( $F < 1$ ). Go MRT and the probability of choice errors did not differ between conditions, although the probability of omission errors was greater in the frequent compared to rare condition ( $F = 5.2$ ,  $p < .05$ ). IGRT was longer in the frequent compared to rare condition ( $F = 5.8$ ,  $p < .05$ ), and longer relative to Go MRT ( $F = 74.5$ ,  $p < .001$ ), although accuracy of responding on ignore-signal trials did not differ between conditions. Overall inhibition probability was greater in the frequent than rare condition ( $F = 8.9$ ,  $p < .01$ ), while linear effect revealed that inhibition probability decreased with an increase in delay ( $F = 101.4$ ,  $p < .001$ ). However, Condition did not interact with Delay (see Figure 7.1, left panel). Plotting inhibition probability as a function of ZRFT appeared to fail to align the inhibition functions (see Figure 7.1, right panel).

**Table 7.1. Means and standard deviations (in brackets) of performance measures for the rare and frequent stop-signal probability conditions.**

	Rare	Frequent
Go MRT (ms)	530.4 (145.6)	554.11 (141.4)
Go SD (ms)	155.7 (82.6)	125.2 (50.8)
Omission Errors (%)	1.0 (1.6)	4.6 (9.2)
Choice Errors (%)	3.6 (2.5)	3.1 (2.5)
SSRT (ms)	240.7 (74.1)	237.9 (65.4)
FSRT (ms)	498.7 (110.5)	521.2 (132.5)
IG Accuracy (%)	84.5 (5.5)	83.3 (7.3)
IGRT (ms)	595.7 (157.7)	654.0 (199.8)

**Abbreviations:** Go MRT = Primary task mean reaction time to go stimuli on no-signal trials; Go SD = Mean within-subject standard deviation of reaction time to go stimuli on no-signal trials; FSRT = Mean reaction time to go stimuli on failed stop trials; SSRT = Mean stop-signal reaction time; IG = Ignore-signal; IGRT = Mean reaction time to go stimuli on ignore-signal trials.



**Figure 7.1. Inhibition probability as a function of stop-signal delay (MRT – x) (left panel) and as a function of ZRFT (right panel).**

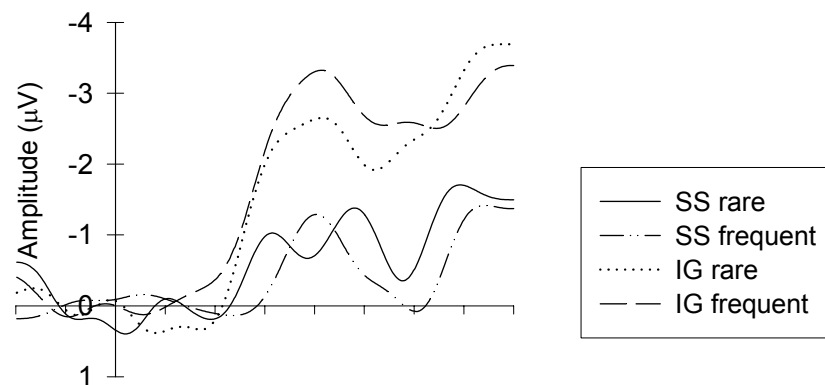
As a test of the independent processes assumption, FSRT was compared to Go MRT (Logan, 1994) and it was found that, across conditions, the former was significantly shorter than the latter ( $F = 14.4, p < .01$ ). There was no interaction between Condition and Trial. Another test is to analyse FSRT between delays. The race model states that FSRT should decrease with stop-signal delay because only the fastest RTs will escape the inhibition process at the earlier delays (Logan, 1994). This was confirmed with a linear contrast effect ( $F = 10.6, p < .01$ ).



## 7.4.2 Lateralised Readiness Potential (LRP)

### 7.4.2.1 The Effect of Stimulus Probability

The LRP was examined to determine the effect of probability on response processing. A main effect of Condition revealed that stimulus-locked LRP amplitude was larger for rare compared to frequent successful stop trials ( $-4.9$  vs.  $-3.7$   $\mu\text{V}$ ), with the same effect for ignore-signal trials ( $-6.0$  vs.  $-5.3$   $\mu\text{V}$ ,  $F = 14.3$ ,  $p = .001$ ; see Figure 7.2). Across conditions, amplitude was larger for ignore-signal compared to successful stop trials ( $-5.7$  vs.  $-4.3$   $\mu\text{V}$ ,  $F = 9.3$ ,  $p < .01$ ). No other LRP measures showed significant effects.<sup>28</sup>

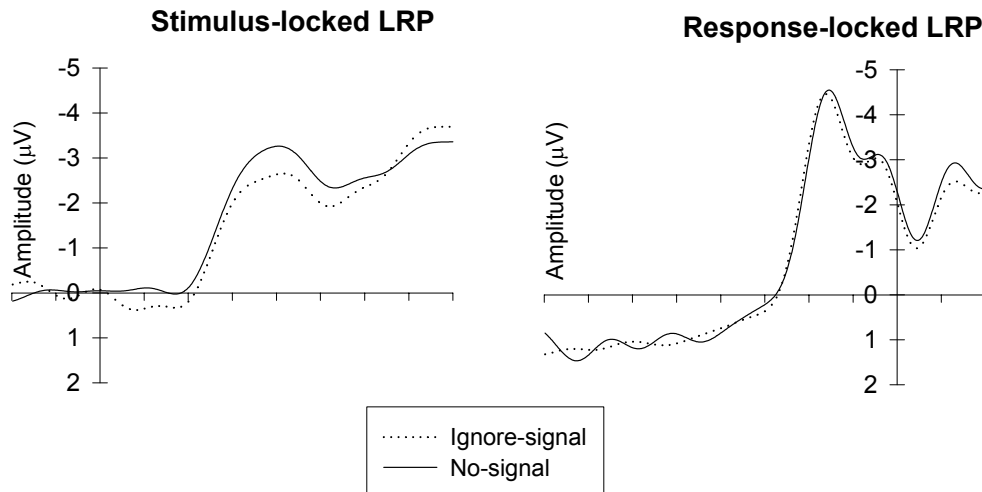


**Figure 7.2. Stimulus-locked LRP waveforms for stop- (SS) and ignore-signals (IG) in the rare and frequent stop-signal probability conditions. Notes: (1) x-axis ticks = 100 ms, (2) vertical bar indicates go stimulus onset, (3) y-axis = +1 to -4, and (4) negative-going amplitude is up.**

<sup>28</sup> Response-locked LRP measures could not be analysed for successful stop trials due the lack of an overt response on these trials.

#### 7.4.2.2 The Effect of the Ignore-signal

The stimulus-locked LRP revealed that onset was longer for ignore-signal compared to no-signal trials (regression method: mean difference = 73.5 ms,  $F = 11.6$ ,  $p < .010$ ; criterion method: mean difference = 72.0 ms,  $F = 12.4$ ,  $p < .011$ ; see Figure 7.3, left panel).<sup>29</sup> This effect did not differ between conditions. For response-locked LRP, the onset-to-RT interval did not differ between trials (regression method:  $F < 1$ ; criterion method:  $F < 1$ ; see Figure 7.3, right panel). No other LRP measures showed significant effects.



**Figure 7.3.** Stimulus-locked LRP (left panel) and response-locked LRP (right panel) for ignore-signal and no-signal trials across conditions. Notes: (1) x-axis marks every 100 ms, (2) vertical bar indicates go stimulus onset, (3) y-axis = +2 to -5, and (4) negative-going amplitude is up.

#### 7.4.2.3 A Central vs. Peripheral Site of Inhibition

To examine the notion that some successful stop trials may be associated with supra-threshold LRP activity (De Jong et al., 1990), indicating a central (i.e. cortically-

<sup>29</sup> Note that no-signal trials occur on 40 % of trials in both rare and frequent stop-signal probability conditions, while ignore-signal trials occurred on 30 and 70 % of trials, respectively. Therefore, the probability of trials was not equated in the statistical comparisons.

located) or peripheral (i.e. downstream from the motor cortex) “site” of inhibition (Band and van Boxtel., 1999; van Boxtel et al., 2001), maximum LRP amplitude on successful stop trials was compared with the threshold value for go trials (see Table 7.2). The LRP threshold for responding was determined for each subject by calculating the amplitude of the individual LRP elicited by go stimuli on no-signal trials at 100 ms prior to Go MRT, in accordance with previous studies who suggest a delay of 80 ms between EMG onset and RT, and a transmission delay of 20 ms (Bekker et al., submitted; de Jong et al., 1990). Across probability conditions, there was a tendency towards maximum amplitude exceeding the threshold value ( $F = 3.5$ ,  $p = .070$ ), however an interaction with Condition revealed that maximum amplitude exceeded the threshold value in the rare stop-signal probability condition only ( $F = 6.7$ ,  $p < .05$ ).

**Table 7.2. Threshold amplitudes of the LRP calculated on no-signal trials and maximum amplitude on successful stop trials separately for the rare and frequent stop-signal probability conditions. Note: (1) measures in  $\mu V$ , (2) standard deviations in brackets.**

	Maximum Amp	Threshold
<b>Rare</b>	-4.91 (2.34)	-3.15 (2.72)
<b>Frequent</b>	-3.69 (2.40)	-3.54 (2.87)

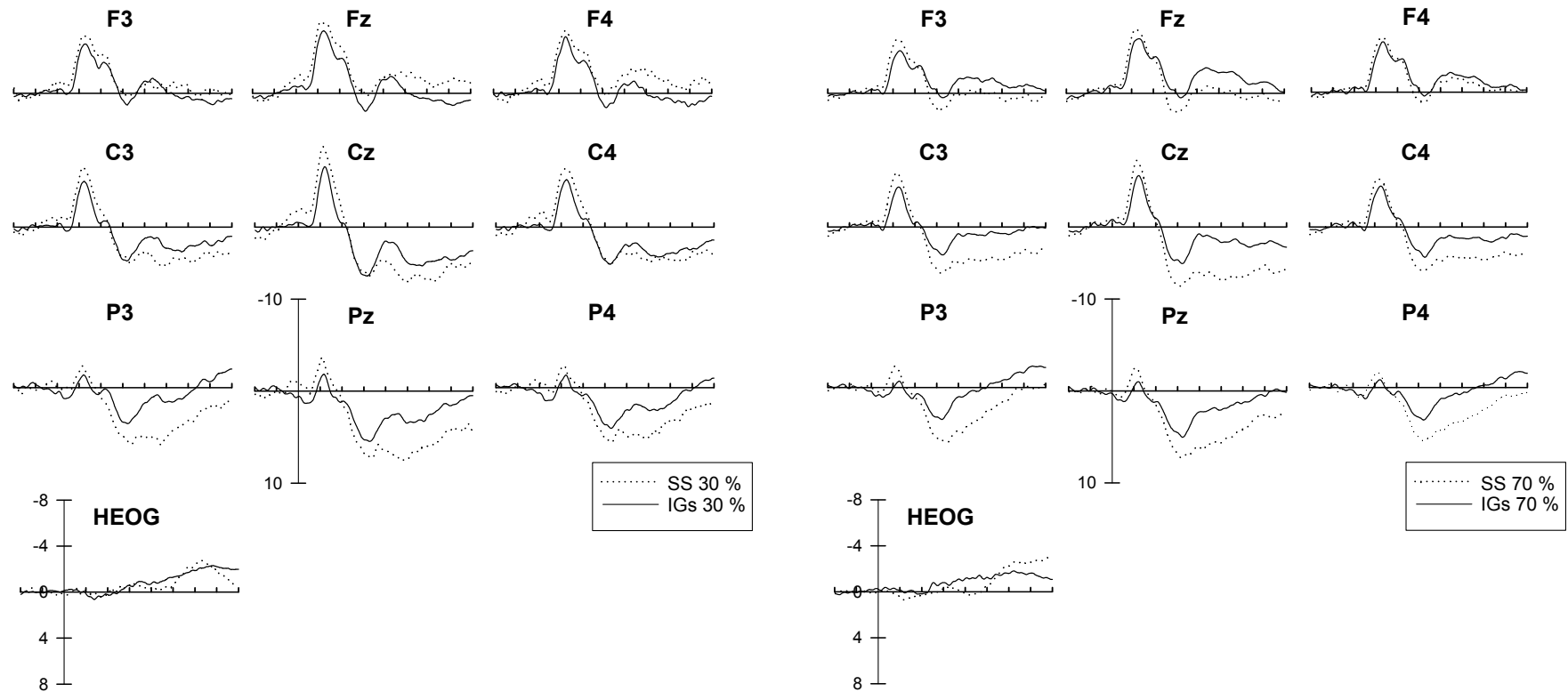
#### 7.4.3 *Successful Stop: ERP Component Analysis*

Figure 7.4 depicts the ERP averages for successful stop and corresponding (slow) ignore-signal trials, for rare (left panel) and frequent (right panel) stimuli. Figure 7.5 offers the opposite perspective with rare compared to frequent stimuli for stop-signal trials (left panel) and ignore-signal trials (right panel). The following section reports effects involving successful stop and corresponding (slow) ignore-signal trials (i.e. 30 % stop-signal vs. 30 % ignore-signal, and vice versa). Means and effect summaries for the following are in Table 7.3. Figure 7.6 plots the significant Trial and Condition main effects for N1, N2 and P3 amplitude.

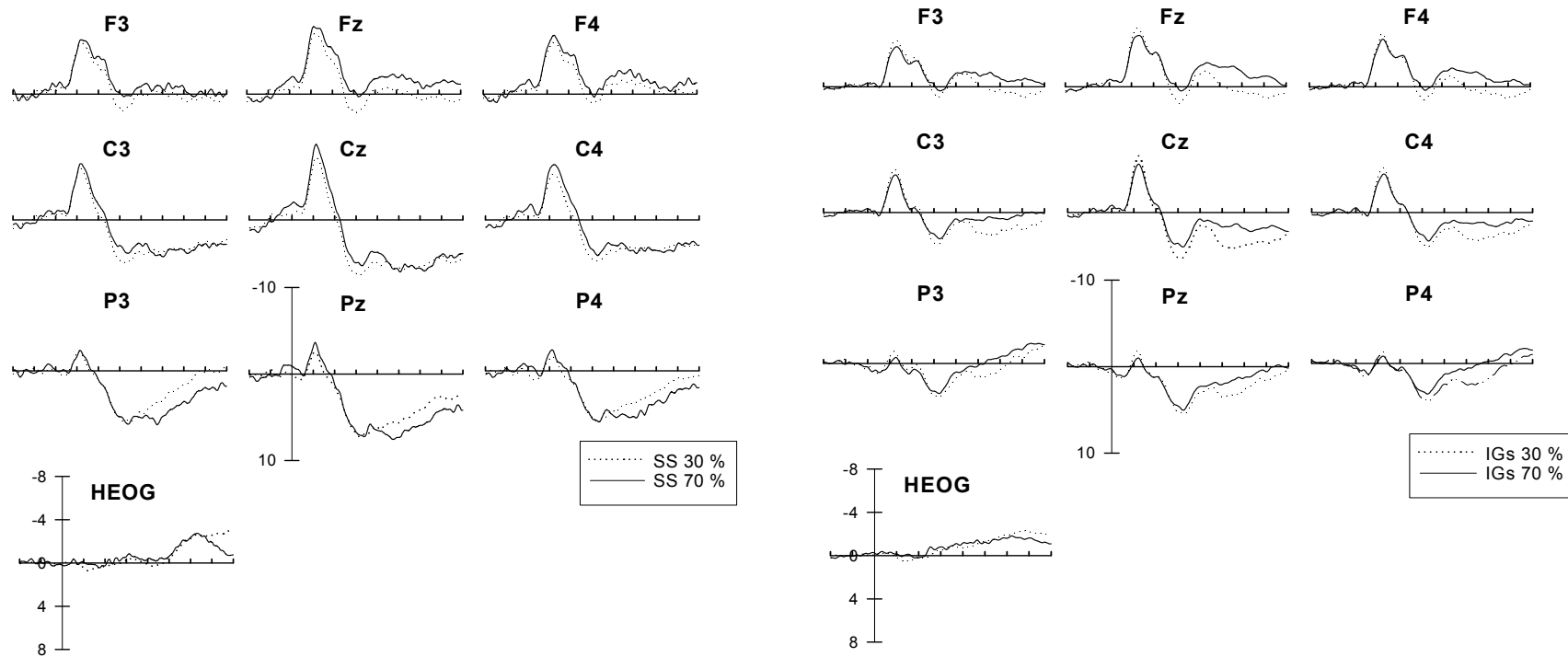
**N1:** N1 amplitude was larger across the scalp for stop- compared to ignore-signals, with this difference largest in the central and midline regions, respectively. Between conditions, N1 was larger across the scalp for rare compared to frequent stimuli, regardless of the trial-type, with this difference also largest in the central and midline regions. There were no interactions between Trial and Condition.

**N2:** Mean N2 amplitude was larger across the scalp for stop- compared to ignore-signals, although this effect was not localised to any particular region. Between conditions, N2 amplitude was larger across the scalp for frequent compared to rare stimuli. There were no interactions between Trial and Condition. With respect to peak latency, N2 peaked later for rare compared to frequent stimuli, regardless of the trial-type.

**P3:** P3 amplitude was larger across the scalp for stop- compared to ignore-signals, with this difference largest in the parietal and left-midline regions, while the midline > lateral effect occurred largely in the central region. There was a tendency ( $p = .052$ ) towards a main effect of Condition, with larger P3 amplitude for rare compared to frequent stimuli, and this difference showing a centrally-maximal midline > lateral effect. An interaction between Trial and Condition revealed a midline > lateral effect in the frontal region for stop-signals that was larger for rare than frequent stimuli, while this effect did not differ between rare and frequent stimuli for ignore-signals; in the parietal region, this effect was larger for frequent than rare stop-signals and the converse occurred for ignore-signals.

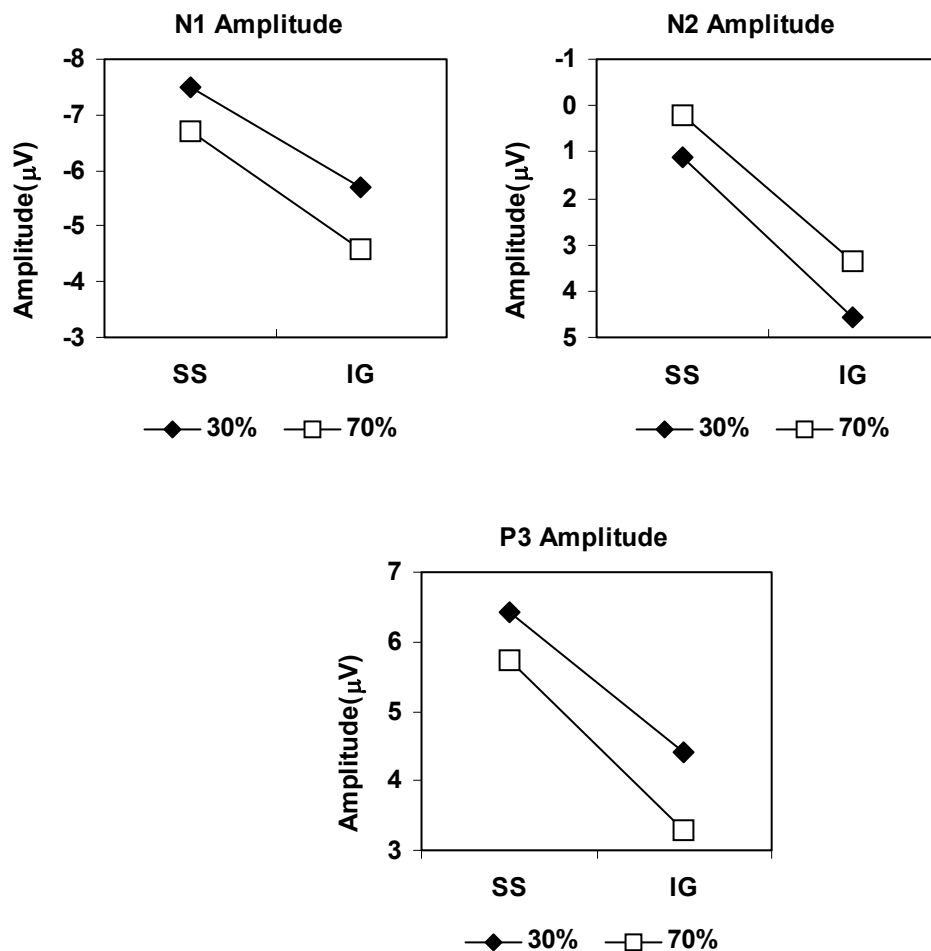


**Figure 7.4.** Grand average stimulus-locked ERP waveforms at nine sites and the horizontal eye channel (HEOG) comparing successful stop (SS) and ignore-stop trials (IGs) for rare stimuli (left panel) and frequent stimuli (right panel). Notes: (1) x-axis ticks = 100 ms, (2) stimulus onset indicated by vertical bar at Pz, (3) y-axis =  $\pm 10 \mu V$ , (4) HEOG y-axis =  $\pm 8 \mu V$ .



**Figure 7.5.** Grand average stimulus-locked ERP waveforms at nine sites and the horizontal eye channel (HEOG) comparing the rare 30% and frequent 70 % probability conditions for successful stop trials (SS; left panel) and ignore-stop trials (IGs; right panel). Notes: (1)  $x$ -axis ticks = 100 ms, (2) stimulus onset indicated by vertical bar at Pz, (3)  $y$ -axis =  $\pm 10 \mu V$ , (4) HEOG  $y$ -axis =  $\pm 10 \mu V$ .

To test the hypothesis that the successful stop P3 reflects an inhibition process that affects response processing (Kok et al., 2004; Ramautar et al., 2004), correlations were performed between P3 amplitude on successful stop trials and LRP measures. A negative correlation was found between P3 at Fz in the rare stop-signal probability condition and stimulus-locked LRP onset-to-peak interval (regression method:  $r = -.41$ ,  $p < .05$ ; criterion method:  $r = -.46$ ,  $p = .01$ ; explained variance 16.9 and 21.2 %, respectively), while P3 at Fz in the frequent stop-signal probability condition showed a tendency towards a relationship with this LRP measure (regression method:  $r = -.32$ ,  $p = .09$ ; criterion method:  $r = -.32$ ,  $p = .09$ ; explained variance 9.9 %).



**Figure 7.6.** Plots of Trial by Condition interactions for N1, N2 and P3 amplitudes show main effects for Trial and Condition, and no interaction between these two factors. Notes: (1) y-axis shows larger amplitudes at the top of the scale depending on the polarity of the component.

**Table 7.3. A summary of the amplitude analysis results for the ERP components to stop- and ignore-signals. Notes: (1) contrast abbreviations for this and the following summary tables are shown below, (2) degrees of freedom for each contrast = 1, 29, (3) all amplitude values are in  $\mu\text{V}$ .**

	Effect	Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>N1</b>	T	SI vs. IG	-7.1 vs. -5.1	26.8	.000
	T x Sag	c vs. f/p	SI: -9.0 to -6.2 vs. IG: -6.4 to -1.5	19.7	.000
	T x Lat	M vs. L/R	SI: -8.2 to -6.5 vs. IG: -5.9 to -4.5	21.0	.000
	T x Sag x Lat	cM to cL/R vs. f/pM to f/pL/R	toSI: -10.6 to -8.1 vs. -7.1 to -5.7 IG: -7.5 to -5.9 vs. -5.0 to -4.2	5.1	.031
	C	Rare vs. Frequent	-6.6 vs. -5.6	5.6	.025
	C x Sag	c vs. f/p	Rare: -8.3 to -5.7 vs. Frequent: -7.1 to -4.9 Rare: -7.6 to -6.1 vs. Frequent: -6.5 to -5.2	6.5	.017
	C x Lat	M vs. L/R	5.2	6.9	.014
<b>N2</b>	T	SI vs. IG	0.7 vs. 3.9	30.7	.000
	C	Rare vs. Frequent	2.8 vs. 1.8	4.5	.042
<b>P3</b>	T	SI vs. IG	6.1 vs. 3.8	10.8	.003
	T x Sag	f vs. p	SI: 3.2 to 7.6 vs. IG: 2.0 to 4.5	8.1	.008
	T x Lat	L vs. R	SI: 5.6 to 5.2 vs. IG: 3.2 to 3.5	8.6	.007
		M vs. L/R	SI: 7.4 to 5.4 vs. IG: 4.8 to 3.4	15.1	.001
	T x Sag x Lat	cM to cL/R vs. f/pM to f/pL/R	toSI: 9.5 to 6.3 vs. 6.5 to 4.9 IG: 6.3 to 4.4 vs. 4.1 to 2.8	14.8	.001
	C	Rare vs. Frequent	5.4 vs. 4.5	4.1	.052
	C x Sag x Lat	cM to cL/R vs. f/pM to f/pL/R	Rare: 8.6 to 5.7 vs. 5.7 to 4.3 Frequent: 7.2 to 5.0 vs. 4.8 to 3.5 Rare SI: 3.8 to 2.8 vs. 9.8 to 7.7 Rare IG: 3.2 to 2.8 vs. 6.1 to 4.4 Frequent SI: 4.3 to 2.9 vs. 8.0 to 6.3	5.8	.022
	T x C x Sag x Lat	fM to fL/R vs. pM to pL/R	Frequent IG: 1.6 to 1.2 vs. 5.3 to 3.5	9.5	.005

**Abbreviations:** for this and subsequent tables, vs. = versus; Sagittal (Sag): C = Condition; T = Trial; f = frontal (mean activity at F3, Fz and F4); c = central (mean activity at C3, Cz and C4); p = parietal (mean activity at P3, Pz and P4); f/p = frontal/parietal (mean activity of F3, Fz, F4, P3, Pz and P4); Laterality (Lat): L = left (mean of activity at F3, C3 and P3); R = right (mean of activity at F4, C4 and P4); M = midline (mean of activity at Fz, Cz and Pz); L/R = left/right (lateral regions; mean of activity at F3, F4, C3, C4, P3 and P4); Lateral by Sagittal interactions: fL = F3; fR = F4; fM = Fz; fL/R = mean of activity at F3 and F4; cL = C3; cR = C4; cM = Cz; cL/R = mean of activity at C3 and C4; pL = P3; pR = P4; pM = Pz; pL/R = mean of activity at P3 and P4; f/pL = mean of F3 and P3; f/pR = mean of activity at F4 and P4; f/pM = mean of activity at Fz and Pz; f/pL/R = mean of activity at F3, F4, P3 and P4.

#### 7.4.4 Successful Stop: Principal Components Analysis

A PCA was performed to examine the component structure of the auditory-evoked ERPs, in particular, activity in the 200 to 250 ms latency range. Cases included successful stop and correct ignore-signal trials for the two conditions across the 17



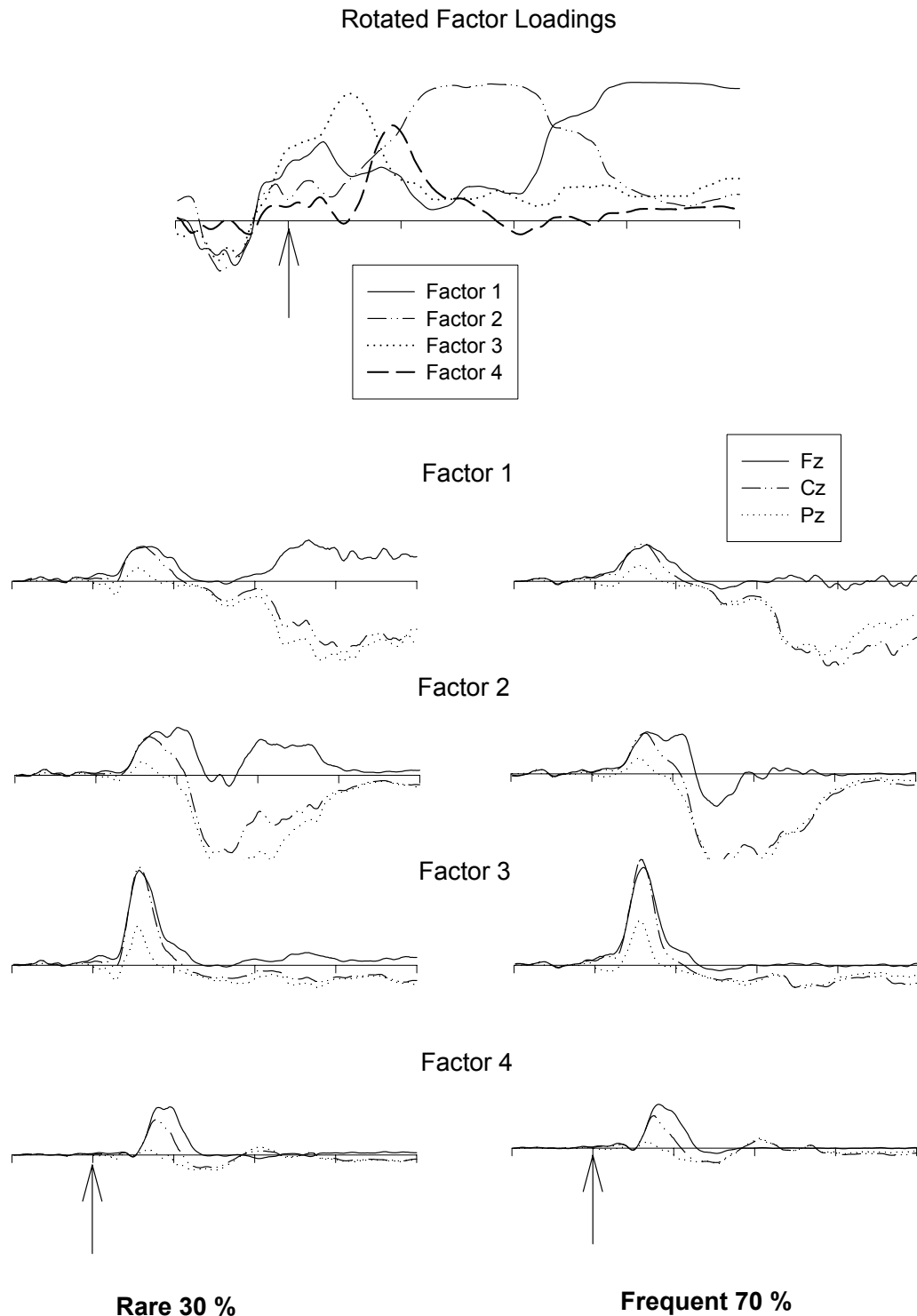
electrode sites<sup>30</sup> for each subject (i.e.  $2 \times 2 \times 17 \times 30 = 2040$  cases) and the variables were 255 time points of the waveform (van Boxtel et al., 1998). This was performed on the covariance matrix, with a Varimax rotation, resulting in the extraction of 4 factors using a scree plot, which explained 94.5 % of the variance in the data (75.0, 15.1, 2.7 and 1.6 %).<sup>31</sup> Figure 7.7 shows the loadings for the extracted factors (top panel) and an estimate of the contribution of each factor to the original waveforms at the midline sites for successful stop trials in the rare 30 % (left panel) and frequent 70 % (right panel) conditions.

Factor 1 was identified as a slow-wave (SW) component, which shows a negative polarity with a fronto-central distribution in the early part of the waveform (0 to 400 ms), and in the late part (400 to 800 ms), a negative polarity in the frontal region and a positive polarity in the centro-parietal region. Factor 2 showed a bi-phasic negative component (N1-N2) in the frontal region and an N1/P3 complex centro-parietal region (P3), with N1 amplitude reduced in the parietal region. Factor 3 reflected the N1 component with a clear fronto-central distribution. Finally, Factor 4 showed an early N2 component with a fronto-central distribution. As can be seen in Figure 7.7 (top panel), the 200 to 250 ms latency range predominantly reflects activity from Factors 2 and 4. This suggests that, within the 200 to 250 ms interval, mean amplitude for successful stop trials reflects the activity of two negative components in the frontal region, and is overlapped by positive components in the centro-parietal region.

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<sup>30</sup> All 17 electrode sites were used to increase the reliability of the PCA-extracted factors.

<sup>31</sup> The scree plot allows one to determine the factor at which the eigenvalue begins to increase (van Boxtel, 1998). A fifth factor (1.1 %), which would have been included if the *eigenvalue equals one* rule was used (van Boxtel, 1998), reflected pre-stop-signal activity identified as residual activity related to the processing of the primary task go stimulus.



**Figure 7.7.** The varimax-rotated factor loadings from the PCA across successful stop and corresponding ignore-signal trials. Also shown is an estimate of the contribution of each factor to the original waveforms at the midline sites for the successful stop trials in the rare 30 % (left panel) and frequent 70 % (right panel) conditions. Notes: (1) Dashes on the x-axis = 200 ms, (2) Stimulus onset indicated by arrows on Rotated Factor Loadings and Factor 4 graphs.

Repeated-measures ANOVAs were performed on the factor scores to examine the main effects of Trial, Condition and the interaction of these two factors across the nine (3 x 3) electrode sites. A main effect of Trial was found for Factor 3 (N1) ( $F = 7.2$ ,  $p < .05$ ), Factor 4 (N2) ( $F = 14.0$ ,  $p < .01$ ), Factor 2 (N1-N2/P3) ( $F = 14.6$ ,  $p < .01$ ) and Factor 1 (SW) ( $F = 7.9$ ,  $p < .01$ ), with larger scores for successful stop compared to ignore-signal trials.<sup>32</sup> However, the SW was the only component that showed a main effect of Condition ( $F = 12.6$ ,  $p < .01$ ) with greater positivity in the rare compared to frequent condition.<sup>33</sup> There were no significant interactions between Trial and Condition.

## 7.5 Discussion

Stop-signal probability was varied in the stop-signal task to determine whether *rare* stop-signals would be associated with greater inhibitory activation than *frequent* stop-signals. It is generally agreed that presenting stop-signals more frequently creates a bias that facilitates inhibition, while stop-signals presented rarely create a bias towards responding (Logan & Burkell, 1986; Ramautar et al., 2004). As varying the probability of a stimulus produces its own corresponding effects on ERPs, it has been difficult to disentangle oddball effects from true inhibitory requirements in previous ERP inhibition studies. Therefore, the present study also presented a task-irrelevant ignore-signal and

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<sup>32</sup> Larger factor scores for negative components indicates larger negative values, while larger factor scores for positive components indicates larger positive values.

<sup>33</sup> Note that the other factors showed topographic differences between conditions, however, the purpose of the analysis was to determine the correspondence between the conventionally-picked components (which only showed Trial and Condition main effects across the nine sites) and the PCA-extracted factors. Therefore, only main effects across the nine sites are reported.

examined the concurrent effect of varying the probability of this stimulus. This design also equated the number of trials containing a tone between probability conditions, thereby avoiding effects due to differences in global auditory stimulation. It was hypothesised that if differences in stimulus probability for stop-signal ERPs reflected the variable recruitment of inhibition processes, these effects would be greater than any probability differences observed for ignore-signal ERPs.

### *7.5.1 Inhibitory Performance*

Firstly, the independence assumption was upheld in this study for both conditions, supporting the validity of the estimated SSRT (but see Band et al., 2003b). In line with previous studies, SSRT remained unaffected by stop-signal probability (Logan & Burkell, 1986; Logan et al., 1984; Ramautar et al., 2004; van den Wildenberg et al., 2003) while inhibition probability was greater for frequent compared to rare stop-signals (Logan & Burkell, 1986; Logan et al., 1984; Ramautar et al., 2004). The inhibition functions, however, did not differ in slope, in contrast to Ramautar et al. (2004). Furthermore, when the inhibition functions were plotted against the ZRFT transformation of the relative finishing times of the go and inhibition processes, the functions were not aligned. This finding suggests that poorer inhibitory control for rarer stop-signals may be due to variability in the latency of the inhibitory response, or the inhibition process being triggered less frequently (Logan, 1994). However, the ZRFT transformation of the inhibition function should be interpreted with caution as it is vulnerable to within-subject variability in the go response, which the transformation is supposed to correct (Band et al., 2003a). Nevertheless, an examination of stop-signal ERPs will provide further insight into differences between conditions in stopping.

### 7.5.2 *Go Response Processes*

While responding on no-signal trials remained relatively unaffected by varying stop-signal probability, responding on ignore-signals trials was slower and the probability of omission errors were greater when stop-signals were presented frequently, which is consistent with previous findings of increased RT with increased stop-signal probability (Logan & Burkell, 1986; Logan et al., 1984; Ramautar et al., 2004). Furthermore, LRP amplitude, which reflects the degree of side-specific response preparation in the motor cortex (Coles, 1985), was larger on successful stop trials for rare compared to frequent stop-signals. These findings show that varying stop-signal probability affected the relative degree of response preparation, and suggest that greater response preparation for rare stop-signal trials was more difficult to inhibit relative to frequent stop-signal trials. However, in another respect, this finding may also indicate that the degree of response preparation, and therefore, the difficulty in inhibiting responses, was equal between conditions, but that responses were merely less inhibited for rare stop-signals. It is difficult to disentangle these two interpretations because LRP amplitude reflects a balance measure between go and inhibition processes (Band et al., 2003a).

The effect of the ignore-signal on response processing was also examined to determine whether this stimulus was actually ignored, or whether it may have been associated with the activation of some inhibitory processes, as longer MRT for ignore-signal compared to no-signal trials would suggest. Onset of the stimulus-locked LRP provides an indication of the duration of perceptual processes that precede side-specific motor preparation, while the interval between the onset of the response-locked LRP and RT reflects the duration of motor-related processes (Hsieh & Yen-Ting, 2003; Osman et al., 2003). It was found that stimulus-locked onset was longer for ignore-signal

compared to no-signal trials, while there was no difference between trials for the onset-to-RT interval. This suggests that longer RT for ignore-signal trials was the result of a longer duration of perceptual processes, and not a longer duration of motor processes. Therefore, the ignore-signal may have momentarily interrupted the perceptual stages of go processing.

To examine the notion that some successful stop trials may be associated with supra-threshold LRP activity (De Jong et al., 1990), indicating a central (i.e. cortically-located) or peripheral (i.e. downstream from the primary motor cortex) site of inhibition (Band and van Boxtel., 1999; van Boxtel et al., 2001), maximum LRP amplitude on successful stop trials was compared with the threshold value for go trials. Findings showed supra-threshold LRP amplitude for some successful stop trials in the rare stop-signal probability condition only. This suggests that when stop-signals were rare, facilitating a bias towards responding, the site of inhibition on some successful stop trials occurred at some point after the response had been released from the primary motor cortex, supporting the notion that inhibition was a more difficult task in the rare condition.

### 7.5.3 *Successful Stop ERP Findings*

Enhanced amplitudes were found for stop-signal compared to ignore-signal trials for each ERP component. This indicated early discrimination between task-relevant and task-irrelevant stimuli that was probably reflected in a component at the N1 latency range. N1 amplitude was larger for successful stops compared to ignore-signals across the scalp, although the difference was largest in the midline. This effect may have reflected the PN component which acts as an early sensory discrimination process, excluding sensory input from further central processing, as manifested in reduced

amplitudes of later components for ignore-signal trials (i.e. N2 and P3) (Hillyard et al., 1973; Näätänen et al., 1978).

In Study II (Chapter 5), it was found that poorer inhibitory control in the selective compared to simple condition was partly due to reduced attention to the stop-signal at early stages of sensory discrimination. Bekker et al. (2005a) found larger N1 amplitude for successful compared to failed stop trials, which they suggested may reflect a greater attentional switch that is determinative for a subsequent successful stop. Filipovic et al. (2000) found that trials requiring the inhibition of either an overt response or response preparation were associated with enhanced N1 amplitude. These authors suggested that the auditory nogo N1 may index the pre-motor decision to inhibit, specifically, the decision to withdraw further attention from the task on that trial, that is, to not prepare or execute a go response. Therefore, early sensory discrimination of the stop-signal at the N1 latency range appears to be particularly important in the subsequent successful stop of a response. However, N1 amplitude was larger for rare compared frequent stop-signals despite inhibition probability being reduced for rare stop-signals. This difference was largest in the central and midline regions, in line with the distribution of the exogenous N1, which has previously been shown to be affected by stimulus probability (Näätänen & Picton, 1987). Therefore, the stop N1 at the scalp surface may be comprised of the attention-related PN, which is required for a subsequent successful stop, and an exogenous N1 that is evoked to a greater extent by novel stimuli.

One of the aims of this study was to examine the notion that N2 may be enhanced for frequent compared to rare stop-signals, thus reflecting the activation of a response selection process when there is a bias towards inhibition (Garavan et al., 2002). While this was found to be the case, ignore-signal trials showed a similar effect

(i.e. frequent > rare) of the same magnitude. It is likely that these effects reflect the overlap of the dominant P3 component, which showed greater amplitude for rare stimuli across the scalp. Therefore, oddball effects could not be dissociated from true inhibitory processing for the small auditory stop N2.

Larger P3 amplitude for rare compared to frequent stop-signals agrees with a number of previous studies examining stop-signal (Ramautar et al., 2004) and nogo probability (Bruin & Wijers, 2002; Donkers & van Boxtel, 2004; Pfefferbaum & Ford, 1988). However, in line with studies examining the effect of varying the probability of the go stimulus in go/nogo tasks (Banquet, 1981; Bruin & Wijers, 2002; Czigler et al., 1996), ignore-signals also evoked greater P3 amplitude when they occurred rarely compared to frequently, and this difference in probability conditions was not larger for stop- compared to ignore-signal trials. Therefore, between-condition differences observed on stop-signals trials cannot be attributed to inhibitory processing, but rather, probably reflect oddball effects. Nevertheless, P3 amplitude showed a different topographic distribution of the rare > frequent effect between stop- and ignore-signal trials. A midline > lateral effect differed between rare and frequent stop-signals across the frontal and parietal regions in a distinct manner to ignore-signal trials. Therefore, successful stop P3 was the only component that was affected differentially by stop- and ignore-signal probability, although not in the anticipated manner.

To examine the notion that successful stop P3 reflects a stop-signal inhibition process that acts on go response processing (de Jong et al., 1990; Kok et al., 2004; Ramautar et al., 2004), correlations were performed with LRP measures. It was found that larger successful stop P3 amplitude was related to a shorter stimulus-locked LRP onset to peak interval, which is believed to reflect the duration that muscles are driven once side-specific response selection has been made (Mordkoff & Gianaros, 2000).



This finding provides some support for the notion that successful stop P3 reflects an inhibition process that suppresses central response activation in the motor cortex (Kok et al., 2004; Ramautar et al., 2004), and also expands on this to suggest that the process acts by decreasing the duration of motor output, rather than by directly reducing the magnitude of activity.

#### 7.5.4 *Slow-Wave (SW) Component*

An interesting finding in the present study that serves to further clarify stimulus probability effects in the stop-signal task was the effect of a PCA-extracted SW component. An examination of the SW factor scores revealed a main effect whereby there was greater positivity for rare compared to frequent stimuli, and this effect did not differ between successful stop and ignore-signal trials. Furthermore, no other factor showed a main effect of Condition, suggesting that the SW may have contributed to a large part of the probability effects observed in the conventionally-quantified components. In the early part of the component, the SW had a negative polarity, while the later part consisted of a positive potential. Generally, negative slow-waves (NSWs) have been associated with a preparedness to respond, resulting from a lowering of thresholds for cortical excitability, while positive slow-waves (PSWs) are believed to be generated when thresholds are set high, reflecting neuronal inhibition and a defacilitation of responding (Birbaumer et al., 1990; Rockstroh, Mueller, Cohen, & Elbert, 1992).

While there is a lack of literature on the NSW because it has been difficult to identify, the PSW has been typically quantified as the mean amplitude in the latter portion of the epoch, that is, in the 400 – 700 ms latency range. The defacilitatory nature of the PSW has led researchers to suggest that the component reflects inhibition

at both neuronal (Howard, Fenton, & Fenwick, 1980) and cognitive or behavioural levels (Podlesny, Dustman, & Shearer, 1984). Furthermore, increases in PSW have been found with increases in task difficulty (Kiefer et al., 1998; Kok, 1986). However, it has also been suggested that the PSW may be functionally related to the P3 in that it reflects additional stimulus processing or a continuation of the target identification process in situations where perceptual demands are high (Kok, 1997). Other researchers suggest the PSW may index the evaluation of the accuracy of a response (Falkenstein, Hohnsbein, & Hoormann, 1994; Overtom et al., 2002). However, in the present study, greater positivity for rare stimuli (regardless of the stimulus type) appears to suggest a general arousal response to a novel event, rather than being related to the greater recruitment of inhibitory processes in the rare stop-signal probability condition (Karlin & Martz, 1973). The following study examines the early negative and late positive components of the slow-wave separately (Chapter 9).

#### 7.5.5 *Other PCA-extracted Factors*

A PCA was performed to examine the component structure of auditory-evoked ERPs in the stop-signal task. In particular, the aim of this analysis was to determine the component structure of activity in the 200 to 250 ms latency range, corresponding to the N2. The PCA has not previously been used as a method of examining ERP component structure in the stop-signal task, and this is probably due to the complexity of the task resulting in a number of overlapping components, as well as a large jitter of component latencies between subjects and conditions (Guthrie, 1990). In the present study, the PCA for successful stop and ignore-signal trials resulted in the extraction of four factors, which were identified as a slow-wave, N1-N2/P3 complex, N1 and N2 components, respectively.

In previous studies, the auditory-evoked N2 was not present in all adult subjects (Study I, Chapter 4; Study II, Chapter 5), due to the fact that this component appears to be reduced in adults (Enoki et al., 1993; Johnstone et al., 1996). The PCA showed that N2 mean amplitude reflected the activity of both negative and positive components. In the frontal region, activity reflected two negative components (Factors 2 and 4). However, in the centro-parietal region, a large P3 component (Factor 2) appeared to overlap the N2. Furthermore, it should be noted that the positive component peaked too late to reflect a P2 component, as is typically evoked to “nogo” standard stimuli in oddball tasks (e.g. Fabiani & Friedman, 1995). Therefore, N2 for auditory stimuli in the stop-signal task was partially overlapped by the P3 component in the centro-parietal region.

At the N1 latency range, a number of individual components have been reported previously (Näätänen & Picton, 1987) and this was confirmed with the PCA, which showed that the successful stop N1 included variance from three factors: Factor 1 (SW), Factor 2 (N1-N2/P3) and Factor 3 (N1). The complex reflected in Factor 2 may correspond to the previously reported N2/P3a for novel auditory stimuli (Banquet, 1981). The P3 component began at 200 ms and peaked at 300 ms post stimulus onset. However, in the centro-parietal region, P3 appeared to be bi-phasic with a second positive component peaking around 400 ms. Two P3 components have previously been reported for auditory stimuli in the go/nogo task (Banquet, 1981; Falkenstein et al., 1995b). Banquet (1981) interpreted an earlier P3 as the centrally-maximal novelty P3a, and a later P3 as the parietally-maximal classic P3b (Squires et al., 1977; Squires et al., 1975), and found that the P3b was more sensitive to global stimulus probability than the P3a, reflecting greater extraction of sensory information from rarer events. It may be

that the later P3 in the current study reflects the P3b (or classic P3) component related to the updating of contextual information (Donchin & Coles, 1988).

#### 7.5.7 *Limitations*

One limitation of this study was that, although bias towards responding was controlled experimentally by varying the probability of the stop-signals, we were unable to control for individual subject differences in performance strategies. That is, some subjects persist in responding cautiously to the primary task so as to increase inhibitory success, while others are impulsive in their style of responding and place less emphasis on the stopping part of the task. Other limitations included the fact that the presentation of the task-irrelevant ignore-signal may have decreased the subjects' sensitivity to the stop-signal. It was previously found in Study II (Chapter 5) where simple and selective stop-signal tasks were compared, that subjects may ignore some stop-signals in the selective stop-signal task.

#### 7.5.8 *Summary*

All components showed greater amplitude for successful stop compared to ignore-signal trials. It is suggested that early sensory discrimination based on the pitch of the tone allowed the stop-signal to be distinguished from the ignore-signal, leading to the exclusion of sensory input from the ignore-signal for further central processing. The N1/P3 complex was enhanced for rare compared to frequent stimuli across the scalp, and N2 showed the converse effect, regardless of the relevance of the stimulus. A PCA revealed a SW component that may have contributed to a large portion of the probability effects observed in the conventionally-quantified components. However,

probability effects did not differ between stop- and ignore-signals for any component. These findings have direct consequences for the interpretation of probability effects as they suggest that modulations of component amplitudes with stop-signal probability do not reflect varying inhibitory requirements, but rather, are the result of oddball effects.

These findings suggest that future stop-signal studies should employ a method other than varying stimulus probability for examining differences in inhibitory processing requirements. For example, one could examine inhibitory processing between different population groups, believed to differ in the relative degree of inhibitory activation or speed. In particular, individuals who display impulsive behaviours, as part of a personality trait or a psychopathology, may have a deficient inhibition process. Therefore, the next study examines inhibitory performance and processing between groups who obtained low and high extreme scores on a personality-based measure of impulsivity (Chapter 9). Subsequently, these two groups are compared to adults with ADHD, a population group believed to suffer from inhibitory control problems (Chapter 10).

## **8. Deficiencies in Response Inhibition**

### **8.1 Chapter Aims**

The primary aim of the next stage of this thesis is to examine deficiencies in response inhibition, specifically as measured by the stop-signal task. Therefore, the aims of this chapter are to: (a) provide an outline of the impulsiveness personality trait, (b) review literature on the relationship between impulsivity and inhibitory control, (c) examine ADHD, with an emphasis on adults with the disorder, and (d) review literature on inhibitory control and associated underlying mechanisms in ADHD.

### **8.2 General Introduction**

Up to this point we have examined the nature of response inhibition through a comparison of the simple stop-signal task with: (a) the inhibition of a prepared, prepotent response in the go/nogo task, and (b) a more complicated form of stop-signal inhibition (selective inhibition), as well as between: (c) fast and slow responders, and (d) low and high stop-signal probability conditions. Logan (1994) suggests that the nature of the stop-signal process can also be elucidated by examining populations that show deficient inhibitory control. Deficiencies in inhibitory control have become central to research in a number of domains, including developmental (e.g. Harnishfeger & Bjorklund, 1994), personality (e.g. Eysenck & Eysenck, 1977) and psychopathology (e.g. Barkley, 1997). The role of response inhibition within personality and psychopathology is of particular interest because of the intrinsic link made by numerous researchers between poor inhibitory control and impulsive behaviours (e.g. Logan et al., 1997; Schachar & Logan, 1990b).

Within personality theory, it has been suggested that individuals who display high degrees of the “impulsiveness” trait appear as though they cannot inhibit behaviour and thoughts (e.g. Eysenck & Eysenck, 1977; Gray, 1991; Logan et al., 1997). Barratt (1993, p. 42) describes the impulsive person as someone who “...acts without thinking, acts on the spur of the moment, (and) is restless when required to sit still...”. Interestingly, these characteristics are similar to the behaviour displayed by impulsive individuals from clinical populations. For example, symptomatic criteria for ADHD include (but are not restricted to): fidgeting and restlessness when required to sit still, acting as if on the “go” or being “driven by a motor”, difficulty waiting for a turn, and being easily distractible (American Psychiatric Association, 2000). As response inhibition aids the cognitive system by providing it with a vital delay in processing to allow the evaluation of consequences and the execution of other functions, a deficiency in this process is believed to result in the above-mentioned symptomatology (Barkley, 1997). However, impulsivity is a multifaceted construct that includes, in addition to deficient response inhibition, rapid information processing, novelty seeking, and an inability to delay gratification (Barratt, 1993; Barratt & Patton, 1983). Therefore, while a response inhibition deficit is a well-established finding in children with ADHD (see Nigg, 2001 for a review), it has not been established whether a similar deficit underlies impulsivity in adults with the disorder, or the impulsiveness personality trait.

The primary questions to be addressed in the next two studies of this thesis are: (1) does a response inhibition deficit underlie the impulsiveness trait in non-clinical subjects, (2) do adults with ADHD suffer from a response inhibition deficit, and (3) can impulsivity in adults with ADHD be conceptualised as existing along a continuum, representing the extreme end of the impulsiveness trait?

### 8.3 Impulsivity

Impulsivity has been variably defined as acting without thinking (Smith, 1952), acting on the spur of the moment without being aware of the potential risks involved (Eysenck, Pearson, Easting, & Allsopp, 1985; Patton, Stanford, & Barratt, 1995), the tendency to act with less forethought than do most individuals of equal ability and knowledge (Dickman, 1993), and acting prematurely and inappropriately to the situation with typically undesirable consequences (Daruna & Barnes, 1993). According to the English Oxford Dictionary (Oxford, 1933), impulsive individuals are characterised by the “sudden or involuntary inclination or tendency to act, without premeditation or reflection” (Definition 3c, “Impulse”, p. 122). Moeller, Barratt, Dougherty, Schmitz, and Swann (2001, p. 1784), however, put together an operational psychological definition of impulsivity as a:

...predisposition towards rapid, unplanned reactions to internal or external stimuli without regard to the negative consequences of these reactions to the impulsive individual or to others.

The key common features of these definitions are that: (a) impulsivity is characterised as an inappropriately short interval between stimulus (whether internal or external) and response, and (b) there is a lack of consideration of the future consequences of these responses. As was noted earlier, response inhibition may provide the cognitive system with a vital delay in processing in order to consider these consequences (Barkley, 1997). Other forms of impulsiveness exist where the individual is fully aware of the consequences, such as in risk-taking and sensation-seeking (Eysenck & Eysenck, 1978; Zuckerman, 1993). However, in order to examine impulsive performance in the stop-signal task (i.e. a greater frequency of failed stops and a longer SSRT), the focus of this thesis, is on the non-deliberate form of impulsiveness that encompasses acting without adequate thought.



### 8.3.1 *Impulsiveness: Personality Theory*

There are four main methods of measuring impulsivity, including: self-report questionnaires, parent and teacher ratings of clinical forms of impulsivity, behavioural laboratory tasks, and psychophysiological measures. Personality theories most commonly use self-report questionnaires which allow the measurement of the frequency of a variety of impulsive behaviours. The disadvantage of this method is that it suffers from the inherent problem of having to rely on an individual's perception and report of their own behaviour. Common inventories include Eysenck's Impulsiveness Questionnaire (IVE; Eysenck, 1993b), and the Barratt Impulsiveness Scale (BIS; Barratt & Patton, 1983). Personality traits representing impulsivity or "impulsiveness", as coined in personality theory, have been determined through factor analytic techniques, which have actually shown impulsiveness to encompass a number of related but distinct components (Nigg, 2000). Originally, a unidimensional model of impulsivity was used by Barratt (1959) to develop the BIS, a 44-item self-report questionnaire. This was later expanded to include three distinct forms of impulsivity that differentiated between motor (acting on the spur of the moment), cognitive (not focussing on the task at hand), and non-planning (focus on the present rather than the future) forms of impulsiveness (Parker & Bagby, 1997; Patton et al., 1995). Eysenck and Eysenck (1977) suggested four factors including narrow impulsiveness, risk-taking, non-planning, and liveliness. However, this was later revised when a factor analysis of impulsivity and sensation-seeking (Zuckerman, 1993) subscales led to the identification of two primary factors: Impulsiveness and Venturesomeness, which were distinct but related constructs ( $r = .3$  to  $.4$ ) (Eysenck et al., 1985). Venturesomeness represents risk-taking behaviour with full awareness, but a disregard of the consequences, while Impulsiveness represents acting without thinking and not being aware of the potential

risks involved in the action. Dickman (1990) had a somewhat different conceptualisation of impulsivity, distinguishing between “functional impulsivity”, which includes the tendency to make quick decisions when this strategy is appropriate to the situation, and “dysfunctional impulsivity”, related to speedy and reflexive decisions which have negative consequences for the individuals.

Although each theorist has developed their own impulsiveness questionnaire, intercorrelations between questionnaires are generally significant, ranging from .40 to .70 (see Barratt & Patton, 1983 for a review; Dickman, 1990; Eysenck, 1993a; Eysenck, 1993b). As a personality-based measure of the impulsiveness trait, the current thesis utilised Eysenck’s IVE Questionnaire (1993b). This allowed comparability with the majority of previous stop-signal studies that have examined the impulsiveness trait (1993b). Furthermore, Eysenck’s Impulsiveness subscale offers high reliability in adults, with coefficients of .84 for males and .83 for females (Eysenck et al., 1985). Finally, it has been shown that Eysenck’s Impulsiveness subscale correlates better with impulsivity-related serotonergic activity than the BIS (Barratt & Patton, 1983; Dolan, Anderson, & Deakin, 2001), suggesting that this scale is more closely related to neuropsychologically mediated aspects of impulsivity. The final point is important for this thesis as ERPs are also used as a means of measuring neural characteristics of impulsivity.

### 8.3.2 *Heritability*

The range of heritability for most personality traits is 40 – 60 % (Zuckerman, 1993). However, a much lower range of phenotypic variance was found to be accounted for in impulsiveness, ranging from 15 to 40 % (Eysenck, 1993a), while Zuckerman’s sensation-seeking trait (Zuckerman, 1993), which is related to

impulsiveness ( $r \sim 0.3 - 0.4$ ) (Zuckerman, 1993), shows an average of 58 % heritability. Thus, there is evidence that impulsiveness shows some genetic heritability.

### 8.3.3 *Neurochemistry*

Impulsive behaviours in a non-ADHD context have been most commonly associated with low levels of serotonergic activity (5-HT) (Fallgatter & Herrmann, 2001; Soubrie, 1986). In particular, reduced 5-HT levels have been associated with impulsive behaviour in aggression, violence, pathological gambling, substance abuse and suicide (Soubrie, 1986). It has been suggested that serotonin may serve the function of inhibition at neural and behavioural levels (Soubrie, 1986; Zuckerman, 1993), while dopaminergic activity (DA) may be associated with behavioural activation in impulsive individuals (Barratt & Patton, 1983; Gray, 1987; Huang, Stanford, & Barratt, 1994). With respect to laboratory measures of impulsivity, reduced serotonin has been related to faster responding and premature responses (Winstanley, Dalley, Theobald, & Robbins, 2004), as well as poorer inhibitory control in the stop-signal task (Oades, Slusarek, Velling, & Bondy, 2002; Overtom et al., 2003).

## 8.4 **Behavioural Inhibition versus Behavioural Activation Systems**

As outlined by the race model, on any particular stop-signal trial, poor inhibitory control may be due to an over-active (i.e. fast) response process, or a deficient (i.e. slow or under-active) inhibition process (see section 1.6; Logan, 1994). Similarly, Gray (1987) introduced a personality theory that distinguishes between a “behavioural activation system” and a “behavioural inhibition system”, reflecting motivationally-mediated systems that respond differentially to cues of reward or punishment. This theory is quite useful in that it is able to explain poor inhibitory control in ADHD and

the impulsiveness trait. ADHD deficits have been linked with an under-active behavioural inhibition system (Matthys, 1998; Quay, 1988, 1997; but see Nigg, 2000), and potentially an over-active behavioural activation system (Quay, 1988; but see Oosterlaan, Logan, & Sergeant, 1998 for evidence showing slow response processes in ADHD), while the impulsiveness trait has been associated with the latter (Gray, 1987). However, Gray's (1987) motivational form of inhibition (i.e. response inhibition driven by fear, anxiety and uncertainty) should be distinguished from executive forms of inhibition (i.e. deliberate response inhibition). While motivational inhibition plays a primary role in personality theory, executive inhibition is emphasised in cognitive theory (Hinshaw, 2003; Nigg, 2000). Executive and motivational inhibition may overlap in some contexts, however, a review of studies shows a tendency towards a lack of relationship between Gray's (1987) behavioural inhibition system and response inhibition performance in the stop-signal task (see Nigg, 2000 for a review; Rodriguez-Fornells et al., 2002; but see Avila & Parcet, 2001 for an exception). Using a factor analysis, Kindlon, Mexxacappa, and Earls (1995) found that executive inhibition in a typical stop-signal task and motivational inhibition in a go/nogo task with reward incentives loaded on separate factors. This demonstrated the distinctiveness of executive and motivational forms of inhibition. Neuropsychologically, both forms of inhibition are related to a fronto-striatal inhibitory system, although executive inhibition emphasises the PFC and its associated cortico-cortico connections while acknowledging subcortical regions, and motivation inhibition emphasises subcortical regions, in particular the limbic system, while acknowledging the PFC (Nigg, 2000). A complete inhibition theory of ADHD and impulsiveness should aim to integrate motivational and executive forms of inhibition (Nigg, 2000), however, the aim of this thesis is to determine the nature of executive inhibition in ADHD and the impulsiveness trait.

Therefore, while we consider the interaction between activation and inhibition systems in the examination of deficient response inhibition, this is constrained to deliberate (top-down), rather than motivationally-driven (bottom-up), inhibition processes.

## **8.5 Inhibitory Control in the Impulsiveness Trait**

### *8.5.1 Deficient Response Inhibition*

Although intercorrelations between self-report questionnaires of impulsivity are generally average to high, the relationship between questionnaires and laboratory measures of impulsivity are quite low (see Barratt, 1983 for a review). Avila et al. (2004) states that this is probably due to the type of task used. A number of tasks purport to measure impulsivity but are actually measuring an aggregate of processes (Tannock, 1998). In contrast, the stop-signal task has been suggested as a good measure of impulsivity as it is associated with the all-or-none inhibition of an ongoing response (Avila et al., 2004; Quay, 1997).

Evidence in favour of a relationship between stop-signal inhibition and the impulsiveness trait comes from studies which have shown higher scores on Eysenck's Impulsiveness subscale (1993b) is associated with an increase in SSRT (Logan et al., 1997) or a reduction in inhibition probability (Marsh, Dougherty, Mathias, Moeller, & Hicks, 2002). Using other personality-based measures of impulsiveness, a significant relationship has been found between stop-signal delay and scores on Dickman's Impulsivity scale in impulsive-aggressive subjects (Vigil-Colet & Codorniu-Raga, 2004). Using the BIS, the motor, but not cognitive, form of impulsiveness was related to SSRT in one study (Gorlyn et al., 2005), although a similar study found no significant relationships (Cheung, Mitsis, & Halperin, 2004). Furthermore, using other

inhibition tasks, the impulsiveness trait has also been associated with impulsive eye blinks in an anti-saccade task (Huang et al., 1994), the frequency of failed stops in the CPT (Marsh et al., 2002) and go/nogo tasks (Stadler & Janke, 2003), and poor inhibitory motor control in a circle tracing task (Bachorowski & Newman, 1985).

A problem with the studies reported thus far is that they used either correlational statistics or a median-split of the sample using Impulsiveness scores to examine the inhibition-impulsivity relationship. Logan et al. (1997) suggests that examining subjects with extreme scores would provide a more sensitive comparison. In response to this issue, Rodriguez-Fornells, Loreno-Seva, and Andres-Pueyo (2002) tested 700 psychology undergraduate students on Eysenck's Impulsiveness subscale (1993b) and obtained the 10 top and 10 bottom scorers of this group. Analyses revealed no significant between-group differences in either the primary or stopping components of the stop-signal task. Similarly, Lijffijt et al. (2004) examined the top and bottom 10 % of scorers on Eysenck's Impulsiveness subscale (1993b) in a group of over 1000 subjects and found no difference in Go MRT or SSRT between groups. However, a meta-analysis across available stop-signal studies (Logan et al., 1997; Lijffijt et al., 2004; Rodriguez-Fornells et al., 2002) revealed a small tendency towards slower SSRTs in high compared to low impulsivity groups (Lijffijt et al., 2004). With the go/nogo task, others have found no relationship between the frequency of failed stops in the go/nogo task and Eysenck's Impulsiveness scores (Horn, Dolan, Elliott, Deakin, & Woodruff, 2003). These findings suggest that very high degrees of the impulsiveness trait may not predispose individuals to impulsive stop-signal task performance.

Neural evidence of deficient response inhibition in the impulsive, non-clinical population is scarce. There are no ERP studies using the stop-signal task to examine the impulsiveness trait and only a limited number of studies that have used the go/nogo and

CPT tasks as laboratory measures of impulsivity. Fallgatter and Herrmann (2001) examined impulsivity and ERPs in healthy subjects during a CPT task and found that the BIS Motor Impulsivity subscale correlated positively with anteriorly-distribution P3 activity for go but not nogo trials. This suggested that impulsivity was related to stronger prefrontal activation during execution of a prepared response. While there were no significant relationships between impulsivity and inhibition-related activity for nogo trials or any performance measures of impulsivity, it was suggested that the stopping component of the task may have been too easy to have evoked inhibitory activation. Nevertheless, a lack of relationship between the inhibition-related P3 and impulsivity has been supported by other studies (Harmon-Jones, Barratt, & Wigg, 1997; Krijns, Gaillard, Van Heck, & Brunia, 1994). In contrast, one study found a reduced P3 anteriorisation effect for nogo trials in a high compared to low impulsivity group, suggesting a deficit in frontal inhibitory processes. However, subjects in this study were severely dependent upon alcohol, which may have confounded results (Fallgatter, Wiesbeck, Weijers, Boening, & Strik, 1998). Therefore, it appears that there is no clear link between the response inhibition process and impulsivity.

Using fMRI, Horn, Dolan, Elliott, Deakin, and Woodruff (2003) examined brain activity during performance of a go/nogo task in healthy adult subjects and found that those with greater scores on Eysenck's Impulsiveness subscale activated the right inferior frontal gyrus and right insula regions to a greater extent in order to successfully stop a response, but showed reduced parietal activation, relative to low scorers. Similarly, Garavan et al. (2002) found greater activation in the ACC in subjects who were more absentminded, using a measure that correlates with the BIS. These findings indicate that impulsive individuals may activate frontal inhibition processes to a greater

extent in order to successfully stop a response (Garavan et al., 2002; Horn et al., 2003), arguing against a response inhibition deficit.

### 8.5.2 *Go Response Processes*

As noted above, impulsivity may be due to an over-active response process (Eysenck, 1993a; Gray, 1987). Performance findings do not appear to support this notion, with a lack of relationship between Impulsiveness scores (Eysenck, 1993b) and Go RT (Logan et al., 1997; Rodriguez-Fornells et al., 2002). However, electrophysiological findings suggest a tendency towards greater response preparation. In one study, subjects performed a visual cued choice-RT task where they were instructed to either respond quickly to the second stimulus on some trials (“speed”) or to delay that response for 1 – 2 s on other trials (“delay”). They found no performance differences between low and high impulsivity groups (divided by a median-split), but larger CNV activity preceding a target stimulus in the high group, particularly in the right hemisphere, suggesting a greater preparedness to respond (Krijns et al., 1994). Enhanced CNV activity in highly impulsive subjects, relative to controls, has also been found during expectation of a nogo stimulus (Jouvent & Pierson, 1998), while other studies have found no relationship between CNV activity and the nogo stimulus (Brown, Fenwick, & Howard, 1989). Again, these findings do not resolve whether impulsivity may be due to excessive response activation, rather than deficient inhibition.

### 8.5.3 *General Findings*

Although there has been little focus on later inhibition-related components such as the N2 and P3, the N1 has been extensively examined as a measure of early sensory-related processes. In particular, the “augmenting/reducing” index (AR), which reflects



either an increase or decrease in N1 amplitude with increasing intensity, has been the focus in impulsivity research. The AR is believed to reflect a sensory gating mechanism that regulates sensory input to the cerebral cortex (Barratt, 1983, 1987; Barratt, Pritchard, Faulk, & Brandt, 1987), with “augmenting” (i.e. an increase in ERP amplitude) reflecting a cortex that “seeks out” sensory stimulation, while reducing reflects a “protectively tuned” system that attempts to attenuate sensory stimulation (Barratt et al., 1987, p. 44). A number of studies have found N1 augmenting in highly impulsive subjects, supported the notion that impulsiveness is associated with “seeking out” stimulation (Barratt, 1987; Barratt et al., 1987; Carrillo-de-la-Pena & Barratt, 1993; Houston & Stanford, 2001). It has been suggested that this response reflects an attempt to compensate for low tonic arousal levels (Eysenck, 1993a; Houston & Stanford, 2001).<sup>34</sup> However, other researchers have found the converse effect with impulsiveness related to “reducing” (see Carrillo-de-la-Pena, 1992 for a review).

Most findings within the oddball task show reduced P3 amplitude in highly impulsive subjects, however, subjects in these studies were also characterised by aggression, or depression, or were regular cocaine abusers (Barratt, Stanford, Kent, & Felthous, 1997; Gerbing, Ahadi, & Patton, 1987; Gerstle, Mathias, & Stanford, 1998; Jouvent & Pierson, 1998; Mathias & Stanford, 1999). In contrast, Harmon-Jones et al. (1997) examined the relationship between P3 amplitude and the different subscales of BIS in an oddball task and found a significant positive correlation for the Motor Impulsiveness subscale only, while Cognitive Impulsiveness and Non-planning Impulsiveness showed negative relationships. Therefore, greater Motor Impulsiveness

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<sup>34</sup> It should be noted that the notion of cortical under-arousal has been applied as a theoretical explanation for the impulsiveness trait and for deficits in ADHD. This association stems from the belief that the effectiveness of stimulant medication rests in their capacity to raise tonic arousal levels to, presumably, a more optimal state (see Rosenthal, 1978 for a review). However, as response inhibition processes are the focus of the current investigations, an examination of tonic arousal levels is beyond the scope of this thesis.

was associated with greater P3 amplitude. Others have found no relationship between P3 and impulsiveness (Barratt, 1987; Huang et al., 1994).

#### 8.5.4 *Summary*

Despite the assumed association between impulsivity and inhibitory control in much of the psychopathological literature, the aggregate of findings suggests an inconsistent relationship between laboratory measures and personality measures of impulsivity, and this appears to be partly due to some methodological issues including: (a) the type of laboratory task used, and (b) the method of examining low and high impulsiveness scores. While some performance studies suggest that a relationship between the impulsiveness trait and deficient response inhibition, electrophysiological studies have shown no relationship, and fMRI studies show *greater* activation of frontal inhibition processes. With respect to response processing, although overt performance does not appear to differ between low and high impulsivity groups, electrophysiological indices suggest greater response preparation in the high group. Furthermore, impulsivity may be associated with a form of sensation-seeking, as reflected in enhanced sensory processing (N1). Therefore, the mechanisms underlying the impulsiveness trait are, at present, uncertain.

It is suggested that the stop-signal task may provide a better method of measuring laboratory forms of impulsivity, while subjects who show extreme high and low scores on the impulsiveness trait will provide a more valid examination of the inhibition-impulsiveness link. Chapter 9 of this thesis examines stop-signal and response-related processing through performance and ERPs between extreme low and high groups differing on Eysenck's Impulsiveness subscale (1993b). Furthermore, as many of samples in the previous ERP studies were also characterised by other health

problems, which may confound findings, the subjects were screened for general health concerns.

## **8.6 Attention-deficit/Hyperactivity Disorder (ADHD)**

ADHD<sup>35</sup> is a neurodevelopmental disorder that affects 3 to 7 % of school-aged children (Tannock, 1998), the essential features of which are developmentally inappropriate levels of inattention, and/or impulsivity and hyperactivity (American Psychiatric Association, 1994). Although some researchers suggest that ADHD symptoms go into remission by the time the child becomes an adult (Hill & Shoener, 1996), several longitudinal studies show the persistence of symptoms into adulthood, although the rate of persistence ranges from 4 to 80 % of cases between studies (Barkley, 1990; Faraone et al., 2000; Mannuzza et al., 1991; Weis, 1986). This large variability is mainly due to between-study differences in the length of follow-up and the definition of symptom persistence (Barkley, 1998; see Table 2, Spencer, Biederman, Wilens, & Faraone, 2002 for a review, p. 4). However, even considering a conservative estimate of symptom persistence into adulthood, it has been suggested that as many as 1 – 3 % of adults may suffer disabling symptoms of ADHD (Roy-Byrne et al., 1997), while in the United States, the prevalence of ADHD amongst adults may reach 6 % (Wender, Wolf, & Wassertein, 2001). Furthermore, data suggest that ADHD in childhood is a risk factor for significant psychiatric, psychosocial or work adjustment difficulties later in life (Barkley, 1998). Therefore, although much of the prior research

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<sup>35</sup> The term used to represent ADHD has gone through a number of changes over the years. The syndrome has previously been known by ‘hyperkinetic reaction to childhood’, ‘minimal brain dysfunction’, ‘attention deficit disorder’, and ‘attention deficit disorder with hyperactivity’ (see Barkley, 1990 for a comprehensive review).

has focused on this disorder in children, there appears to be just as great a need for an understanding of ADHD in adults.

### 8.6.1 *Diagnosis in Children*

The Diagnostic and Statistical Manual of Mental Disorders – 4<sup>th</sup> Edition (Text Revision; DSM-IV-TR; American Psychiatric Association, 2000) defines ADHD as a Disruptive Behaviour Disorder characterised by on-going and developmentally inappropriate levels of Inattention, Hyperactivity-Impulsivity, or both, occurring in several settings. Table 8.1 shows the criteria outlined by the DSM-IV-TR (American Psychiatric Association, 2000) that fall under these dimensions. Symptoms are reported to cluster to yield three subtypes of ADHD in children: (1) predominantly inattentive (at least 6 out of 9 symptoms from the Inattention dimension), (2) predominantly hyperactive/impulsive<sup>36</sup> (at least 6 out of 9 symptoms from the Hyperactivity-Impulsivity dimension), and (3) the combined subtype (at least 6 Inattentive symptoms and at least 6 Hyperactivity-Impulsivity symptoms). To receive a diagnosis of ADHD, symptoms must have persisted in the individual for at least 6 months at a degree that is maladaptive and developmentally inconsistent. In addition to satisfying the above criteria (labelled Criteria A), symptoms must have: (B) been present prior to 7 years of age, (C) caused impairment in two or more settings (e.g. in school or work and at home), (D) caused clearly significant impairment in social, academic, or occupational functioning, (E) not occurred exclusively during the course of, and are not better accounted for, another psychiatric disorder (American Psychiatric Association, 2000).

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<sup>36</sup> It should be noted that the validity of the predominantly Hyperactive-Impulsive subtype has been questioned by a number of researchers due to the fact that it is mainly found in very young children. It has been suggested that individuals diagnosed with this subtype may actually fall under the combined subtype, with inattention symptoms unnoticed until the child reaches school age (Barkley, 1997).

**Table 8.1. The DSM-IV-TR symptom criteria for the diagnosis of ADHD.**

<b>Dimension</b>	<b>Symptoms</b>
<b>Inattention</b>	<ol style="list-style-type: none"> <li>1. Often does not seem to listen when spoken to directly</li> <li>2. Often does not follow instructions and fails to finish schoolwork, chores, or duties in the workplace (not due to oppositional behavior or failure to understand instructions).</li> <li>3. Often has trouble organizing activities.</li> <li>4. Often avoids, dislikes, or doesn't want to do things that take a lot of mental effort for a long period of time (such as schoolwork or homework).</li> <li>5. Often loses things needed for tasks and activities (e.g. toys, school assignments, pencils, books, or tools).</li> <li>6. Is often easily distracted.</li> <li>7. Is often forgetful in daily activities.</li> </ol>
<b>Hyperactivity</b>	<ol style="list-style-type: none"> <li>1. Often fidgets with hands or feet or squirms in seat</li> <li>2. Often gets up from seat when remaining in seat is expected.</li> <li>3. Often runs about or climbs when and where it is not appropriate (adolescents or adults may feel very restless).</li> <li>4. Often has trouble playing or enjoying leisure activities quietly.</li> <li>5. Is often "on the go" or often acts as if "driven by a motor".</li> <li>6. Often talks excessively.</li> </ol>
<b>Impulsivity</b>	<ol style="list-style-type: none"> <li>1. Often blurts out answers before questions have been finished</li> <li>2. Often has trouble waiting one's turn.</li> <li>3. Often interrupts or intrudes on others (e.g., butts into conversations or games).</li> </ol>

### 8.6.2 *Adulthood*

The DSM-IV-TR (American Psychiatric Association, 2000) states that the same criteria may be used to diagnose ADHD in adults, however, it should be noted that no adults were included in the ADHD field trials for the DSM-IV (American Psychiatric Association, 1994; see Kubose, 2000). Adults with ADHD may present as those that were diagnosed as children and continue to show ADHD symptoms, and those that were never diagnosed as children. In the latter group, because ADHD is accepted as having an onset in childhood, clinicians perform a retrospective diagnosis that looks for a childhood history of ADHD symptoms with a continuing presence into adulthood. Specifically, they attempt to discern that current symptoms are clinically severe in terms

of dysfunction, that they are continuous, and that they are unrelated to stress or crisis (NSW Health Pharmaceutical Services Branch, 2003). Recently, a number of researchers are also using supplementary checklists specifically designed for adults, including the ADHD Self-Report Scale for adults (ASRS) (Adler & Cohen, 2003), Conners Adult ADHD Diagnostic Interview for the DSM-IV (Conners, Epstein, & Johnson, 2001), the Wender Utah Rating Scale (WURS) (Ward, Wender, & Reimherr, 1993), and the Brown Attention-Deficit Disorder Scale (Brown, 1995).

As most adults exhibit fewer ADHD symptoms with time, it has been suggested that the DSM-IV-TR (American Psychiatric Association, 2000) criteria may be too stringent to detect the disorder in adults, even though the impairment caused by the remaining symptoms becomes more pronounced (Barkley & Gordan, 2000). One four-year longitudinal study in children with ADHD revealed a decline of symptoms in the Hyperactivity-Impulsivity dimension but no change in the frequency of inattentive symptoms with increasing age (Hart, Lahey, Loeber, Applegate, & Frick, 1995). Impulsivity appears to remain a distinguishing characteristic between adults with ADHD and controls (Bekker et al., in press; Bekker et al., submitted; Feifel, Farber, Clementz, Perry, & Anllo-Vento, 2004; Nigg, 2002; Ossmann & Mulligan, 2003; see section 8.7.1 for a review). Other researchers suggest that while overt hyperactivity diminishes over time, evolving into more internal feelings of restlessness, impulsivity remains as one of the most serious of the symptoms clusters (see Barkley & Gordan, 2000; Rubia et al., 2003; Weis, 1986 for a review). For example, adults with ADHD rate themselves as possessing more impulsive personality traits and have greater problems in acting appropriately in social situations, relative to controls (see Weis, 1986 for a review). Using quantitative EEG, it has been shown that reduced beta activity in children with ADHD (e.g. Clarke, Barry, McCarthy, & Selikowitz, 1998; Clarke, Barry,

McCarthy, & Selikowitz, 2001b) normalises in adulthood, reflecting the reduction of hyperactivity, but that elevated theta activity remains, reflecting the persistence of impulsivity into adulthood (Bresnahan, Anderson, & Barry, 1999; Bresnahan & Barry, 2002).

It has been suggested that the development of hyperactivity into less noticeable feelings of restlessness into adulthood may muddy the pool of true inattentive individuals with sub-threshold combined subtype individuals (Barkley & Gordan, 2002). Although some researchers have attempted to classify adults with ADHD into the DMS-IV-TR subtypes, the presence of distinct subtypes has not been validated in adult ADHD (Kubose, 2000), and findings show few differences in cognitive functioning between adults qualifying for different subtypes (Barkley, Murphy, & Bush, 2001; Murphy, Barkley, & Bush, 2001). This is in contrast to the vast literature showing qualitative differences between the ADHD subtypes in children (e.g. Clarke, Barry, McCarthy, & Selikowitz, 2001a). Therefore, adults with ADHD are unlikely to fall into clear and distinguishable subtypes (Wolf & Wassertein, 2001).

A key difference that is observed between children and adults with ADHD is the deferring gender ratio. In children, boys outnumber girls by 3:1 (Tannock, 1998), however, in adults, this gender difference is less pronounced (Faraone et al., 2000). Faraone et al. (2000) suggests that these figures may reflect an under-diagnosis of girls with ADHD, who may be less likely to exhibit noticeable externalising symptoms. Therefore, a greater number of females may be expected in a sample of adults with ADHD compared to children.

### 8.6.3 *Co-morbidity*

A common feature of ADHD in children and adolescents is the presence of co-morbid conditions. Similarly, in clinically-referred adults, there is a higher frequency of

comorbid major depression (16 – 31 %), oppositional defiant disorder (24 – 35 %) and conduct disorder (CD) (17-25 %) than would be due to chance alone (see Barkley & Gordan, 2000 for a review). Given that CD is a precursor for antisocial traits, 7 – 18 % of adults with ADHD are estimated to develop a full diagnosis of antisocial personality disorder (Biederman et al., 1993), while 32 – 53 % show lifetime alcohol dependence, and 8 – 25 % show some form of other substance dependence or abuse (Barkley, Murphy, & Kwasnik, 1996; Biederman et al., 1993; Roy-Byrne et al., 1997). Like children with the disorder, learning disorders also appear to be a major issue for adults with ADHD with the prevalence estimated to be 40 % (Barkley & Gordan, 2000). The high degree of co-morbidity in adults (and children) with ADHD makes finding a “pure” sample difficult; therefore generalisation across studies may be difficult as most research may be confounded in this manner.

#### *8.6.4 Etiology*

There is no single aetiology that has been identified for ADHD. Extensive reviews indicate a complex combination of environmental, genetic and biological factors (Spencer et al., 2002). Mick et al. (2002) examined prenatal and perinatal risk factors for developing ADHD and found that exposure to cigarettes or alcohol in utero, as well as low birth weight, increased the likelihood of developing ADHD by 2 to 3 times. However, the greatest risk factor, which increased the likelihood of ADHD by 8 times, was having a parent with ADHD, supporting a genetic heritability for the disorder. In a review of studies, Spencer et al. (2002) found the heritability to vary from 60 to 91 %, with an average of 75 %.

Genetic studies have most commonly implicated dopaminergic receptor genes as underlying ADHD (Faraone et al., 2000; Spencer et al., 2002), although the disorder is



likely to result from combination of genes (e.g. Maher, Marazita, Ferrel, & Vanyukov, 2002). In particular, the 7-repeat allele of the D<sub>4</sub> dopamine receptor gene is a defective gene that has been found in 50 – 60 % of the ADHD population (versus 30 % of general population) (Faraone et al., 2000; Spencer et al., 2002). This has been the strongest genetic evidence to-date, with 8 out of 14 studies replicating the effect (Rubia, 2002). Furthermore, an association has been found between ADHD and the dopamine transporter (DAT1) (Cook et al., 1995), with one study finding that hyperactive-impulsive symptoms were associated with a greater loading of the DAT1 high-risk allele and that this association increased with symptom severity (Waldman et al., 1998). Therefore, although environmental factors may contribute to ADHD, a large body of evidence argues for strong genetic heritability.

#### 8.6.5 *Neurochemistry*

The high response rate of both children and adults with ADHD to stimulant medications, which act as DA and noradrenergic (NA) agonists, has implicated catecholamine pathways as central to ADHD deficiencies (Pliszka, McCracken, & Maas, 1996). Fronto-striatal inhibitory circuits, which have been implicated as deficient in ADHD (e.g. Casey et al., 1997), appear to be predominantly driven by NA and DA activity (Zametkin & Rapoport, 1987). Generally, ADHD has been associated with greater levels of DA activity in striatal areas, which may lead to excessive motor activity (Pliszka et al., 1996), although frontal executive dysfunctions may reflect a deficiency in DA at prefrontal synapses (Pliszka et al., 1996; Solanto, 2002). Desipramine and imipramine, which block the reuptake of norepinephrine but have no effect on DA systems, are highly effective in ADHD treatment, emphasising the role of the NA system in underlying attention-related ADHD deficits (Biederman & Spencer,

1999; see Pliszka et al., 1996 for a review). Finally, serotonin has also been implicated in mediating hyperactive-impulsive ADHD behaviours (Oades, 2002; Quist & Kennedy, 2001), however, findings have not shown a consistent relationship (Kruesi et al., 1990; Oades et al., 2002).

## 8.7 Inhibitory Control in ADHD

The name Attention-deficit/Hyperactivity Disorder implies a core deficit in attention (see Douglas, 1972). However, investigations have yielded little evidence for any impairments in attentional processes (Schachar, 1991; Schachar, Mota, Logan, Tannock, & Klim, 2000; Sergeant, 1990; Sergeant, Oosterlaan, & Van der Meere, 1999; van der Meere, 1988). Rather, cognitive deficits in adults with ADHD are predominantly found in frontal executive functions such as planning, working memory, set shifting, response selection and inhibition (Hervey, Epstein, & Curry, 2004; Johnson et al., 2001; Pennington, 1996). Therefore, current models of ADHD have shifted focus to the domain of frontal executive functions (Pennington, 1996), and within that domain, response inhibition (Barkley, 1997; Quay, 1997; Sergeant, 2000).<sup>37</sup>

Some researchers suggest a more general impairment of frontal executive functions in ADHD that includes, but places no specific emphasis on, response inhibition (Pennington, 1996). Support for this position comes from findings that adults with ADHD show impairments across a diverse range of executive functions, with no particular emphasis on one specific function (Hervey et al., 2004). In contrast, Barkley (1997) put forward a theory of ADHD in children (specifically for the

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<sup>37</sup> The author acknowledges that competing models of ADHD emphasise other factors, including state moderators such as arousal, activation or effort (Sergeant, Oosterlaan, & van der Meere, 1999), regulation (Douglas, 1999), vigilance systems (Swanson et al., 1998), and response style (Sonuga-Barke, Saxton, & Hall, 1998). However, an assessment of these factors is beyond the scope of this thesis, the focus of which is on response inhibition.

combined subtype) that attempts to unify ADHD executive deficits, attributed to the orbitofrontal regions of the PFC and its reciprocal connections with the ventromedial striatum, by proposing a core deficit in response inhibition. According to Barkley (1997), response inhibition is central to efficient cognitive functioning, with poor inhibitory control leading to secondary deficits in executive functions, consisting of: (a) working memory, (b) self-regulation of affect, motivation and arousal, (c) internalisation of speech, and (d) reconstitution. These functions permit motor control and fluency, affording effective self-regulation and adaptive functioning. Under this view, inhibition suppresses the immediate (prepotent, ongoing or competing) response, allowing a vital delay in cognitive processing for the performance of the secondary executive functions. This position is supported by a review of the child ADHD literature that shows a response inhibition deficit as the most pronounced effect (see Bayliss & Roodenrys, 2000; Nigg, 2001 for a review).

Thus, a response inhibition deficit is an essential feature of ADHD in children, whether it be the core deficit, or one of many. However, it is unclear whether this may be the case in adults with the disorder. The following section reviews the literature on response inhibition in adults, and in relevant areas, in children, with ADHD.

### *8.7.1 Deficient Response Inhibition*

Poor inhibitory control on stop-signal trials can be due to either an over-active (i.e. fast) response process, or a deficient (i.e. slow or under-active) inhibition process (Logan, 1994). The general consensus among researchers is that poor inhibitory control in ADHD is due to a slow inhibition process (Tannock, 1998). This is supported by a meta-analysis of eight stop-signal studies which found robust evidence for a longer SSRT in children with ADHD (Oosterlaan et al., 1998). Similarly, SSRT has been

found to be longer in adults with ADHD compared to age-matched controls (Aron et al., 2003a; Bekker et al., in press; Bekker et al., submitted; Murphy, 2002; Wodushek & Neumann, 2003). The average effect size found by Oosterlaan et al. (1998) ( $d = .64$ ) in the meta-analysis of SSRT in children with ADHD was similar to that found by Epstein (2001) for SSRT in adults with ADHD ( $d = .58$ ). This suggests that adults with ADHD may be characterised by a similar response inhibition deficit to that found in children. In fact, in a recent meta-analysis of stop-signal task performance in children and adults, Lijffijt, Kenemans, Verbaten, and van Engeland (2005) found that the response inhibition deficit, as shown by a longer SSRT, was even more pronounced in adults. While one stop-signal study failed to find a significant difference between groups for SSRT, this was attributed to a small sample size reducing the statistical power of the comparison (see Epstein et al., 2001). Therefore, like children with ADHD, adults with the disorder also appear to suffer from inhibitory control problems, showing a slower inhibitory response.

The link between response inhibition deficits and ADHD-related symptoms of impulsivity is supported by findings using drug treatments in ADHD. In particular, methylphenidate, a stimulant used in ADHD treatment which mediates catecholamine release, has been shown to decrease SSRT in children (Bedard et al., 2003; Tannock et al., 1995; Tannock et al., 1989) and adults (Aron et al., 2003a; Overtom et al., submitted). Similarly, modafinil, a “waking” agent that is believed to promote the release of histamine, has also been shown to reduce SSRT in adults with (Turner, Clark, Dowson, Robbins, & Sahakian, 2004) and without ADHD (Turner et al., 2003). Therefore, the concurrent amelioration of ADHD symptoms and response inhibition deficiencies with medication supports the notion that deficient response inhibition may actually be tied to ADHD symptomatology.

Brain imaging evidence of a dysfunction in fronto-striatal inhibitory circuits is abundant in the child ADHD literature, with reduced (Casey et al., 1997) or abnormal (Durstun et al., 2003) activation of the PFC and basal ganglia consistently characterising children with ADHD (Castellanos et al., 1996). In adolescents with ADHD, an inhibition process localised to the right frontal region has been shown to be deficient, relative to age-matched controls (Rubia et al., 1999), while this process appears to develop with increasing age in healthy controls, suggesting a dysmaturation of the frontal cortex in ADHD (Rubia, 2002; Rubia et al., 2000). In adults with ADHD, deficient frontal-striatal inhibitory circuits have been implicated through findings of poor inhibitory control of saccadic eye movements in ADHD groups, relative to controls (Feifel et al., 2004; Nigg, 2002; Ross, Harris, Olincy, & Radant, 2000). However, brain imaging studies of adults with ADHD show evidence of compensatory responses with greater activation in subcortical regions to compensate for deficient PFC activation (Schweitzer et al., 2004), or a frontal-insular network in place of the ACC during a cognitive inhibition stroop task (Bush et al., 1999), resulting in comparable overt task performance.

There are only two studies to-date that have measured ERPs in adults with ADHD during performance of an inhibition task, both of which are relatively new, underscoring the need for research in this area. Bekker et al. (submitted) presented auditory stop-signals on 40 % of trials in a simple stop-signal task to a group of adults with ADHD and controls matched for age and gender. They found impaired processing at both early sensory and later inhibitory stages. An examination of N1 in the 80 – 124 ms interval at FCz revealed greater amplitude for successful compared to failed trials in the control, but not the ADHD, group. This effect was interpreted as reflecting a deficiency in adults with ADHD in the attentional modulation of the auditory cortex to

stop-signals. That is, the impact of the stop-signal on the auditory cortex was not determinative of subsequent inhibitory success. Therefore, poor inhibitory control in adults with ADHD was partly attributed to deficits in the early sensory analysis of the stop-signal.

In the same study, the mean amplitude between 136 and 352 ms (at Cz), which was interpreted as containing the stop P3, was more positive for successful than failed stop trials in the control group, while this effect was reduced in the ADHD group (Bekker et al., submitted). The authors suggested that this effect was not due to reduced stop P3 amplitude in the ADHD group per se, but rather, reflects the delayed peak latency of the stop P3. An examination of Figure 1 in this study suggests no difference in successful stop P3 peak amplitude between groups. Therefore, a delayed P3 may have reflected a less efficient inhibition system that contributed to a longer SSRT in the ADHD group.

During a CPT, Fallgatter et al. (2005) examined the Nogo-anteriorisation effect, which is believed to reflect an ACC-mediated measure of response control or inhibition, in adults who suffered from ADHD in childhood relative to controls. They found that the Nogo-anteriorisation effect and the fronto-central P3 maximum for nogo trials were both reduced in adults with childhood-ADHD compared to controls. The findings indicated that ADHD, even in adulthood, is associated with prefrontal response inhibition or control dysfunction.

In children, a response inhibition deficit has manifested somewhat differentially between studies. Reduced N2 amplitude in children with ADHD compared to age-matched controls, particularly in the right frontal region, has been associated with an under-active response inhibition process (Pliszka et al., 2000), or a slower inhibitory response (Dimoska et al., 2003). In contrast, Overtom et al. (2002) suggested that

reduced fronto-central P3 amplitude in children with ADHD compared to controls reflected a deficient frontal inhibition process that led to reduced inhibition probability and a longer SSRT. In Dimoska et al. (2003), however, when inhibition probability was equated between groups, stop P3 amplitude did not differ. Furthermore, a closer examination of Figures 1 and 2 in Overtom et al. (2002, pp. 672 and 673) show an unreported N2 that appeared reduced in the ADHD compared to control group. Therefore, in children with ADHD, reduced N2 amplitude may contribute to a slower inhibitory response (Dimoska et al., 2003), while both N2 and P3 may be related to reduced inhibition probability (Overtom et al., 2002; Pliszka et al., 2000).

#### 8.7.2 *Selective (Stop/No-stop) Inhibition*

Although selective inhibition has not been examined in adults with ADHD, in children with ADHD, Bedard et al. (2003) found a slower inhibitory response and a more variable go response, but no difference in response speed, relative to controls. Furthermore, when children with ADHD were treated with methylphenidate, this had the effect of decreasing SSRT and reducing response variability, but *increasing* response speed (Bedard et al., 2003). Therefore, similar to findings in simple stop-signal tasks, children with ADHD also suffer from response inhibition deficits in selective versions of the task, and these deficits may be ameliorated by stimulant medication. However, there was no direct comparison of simple and selective inhibition. Furthermore, although selective inhibition is associated with increased cognitive workload (i.e. retaining the stimulus-response relationship in working memory) and additional processes (i.e. related to stimulus discrimination) (Bedard et al., 2003; Logan, 1994; van den Wildenberg & van der Molen, 2004b), there have been no studies to-date that have examined selective inhibition in adults with ADHD.

Previously it was found in Study II (Chapter 5) that non-clinical adults perform simple and selective stop-signal tasks similarly, with activation of the same, non-selective inhibitory response. This was reflected in a similar SSRT and scalp distribution of the successful stop P3 between conditions. However, if adults with ADHD have difficulties dealing with greater cognitive workloads (see Hervey et al., 2004 for a review), inhibitory control may be impaired to a greater extent in selective than simple conditions. Chapter 10 examined this issue through a within-subject comparison of simple and selective inhibition in adults with ADHD.

### 8.7.3 *Go Response Processes*

It has also been found that children with ADHD have problems with the go response process, as indicated by slow and variable responding in the stop-signal task (Kuntsi, 2001; Oosterlaan & Sergeant, 1996; Schachar et al., 2000; Scheres, 2001). In contrast, adults with ADHD have been shown to respond faster than controls in some studies (Aron et al., 2003a; Murphy, 2002), and not differ from controls in others (Bekker et al., in press; Ossmann & Mulligan, 2003). This suggests enhanced or normal, rather than deficient, response processing. Bekker et al. (submitted) examined the LRP and although they found larger amplitude for fast compared to slow responses within subjects, there was no difference between ADHD and control groups. Therefore, in adults with ADHD, impulsivity does not appear to be the result of over-active response processing (Quay, 1988; Sergeant, Guerts, Huijbregts, Scheres, & Oosterlaan, 2003).

Lijffijt et al. (2005) found that a slower SSRT in adults occurs independently of response processing, as evidenced by a disproportionate elongation of SSRT relative to Go RT (Bekker et al., in press; Ossmann & Mulligan, 2003) and the finding that



methylphenidate and modafinil improve SSRT, but leave Go RT unaffected (Aron et al., 2003a; Lijffijt et al., submitted; Overtoom et al., 2003). It has been suggested that within-subject variability in responding may be a distinguishing feature of ADHD performance in children (see Oosterlaan et al., 1998 for a review) and adults (see Hervey et al., 2004 for a review; but see Ossmann & Mulligan, 2003 for an exception). Furthermore, adults with ADHD have been found to show a greater likelihood of committing errors of choice, which is believed to reflect impulsive responding (Quay, 1997), in some studies (Aron et al., 2003a; Bekker et al., in press), but not in others (Epstein et al., 2001; Ossmann & Mulligan, 2003).

#### 8.7.4 *Error-related Processes*

A typical finding in the trial following an error is the slowing of RT (Falkenstein et al., 2000). Children with ADHD, however, show reduced slowing, relative to controls, which has been interpreted as an impairment in error-monitoring (Schachar et al., 2004). However, there are no ERP studies that have explicitly examined error-related processing either in children or adults with ADHD.

Although not reported, an examination of Figure 1 in Bekker et al. (submitted) shows a reduced failed stop N2 in adults with ADHD relative to controls. As shown in Study III (Chapter 6), failed stop N2 reflects the aggregate of stop-signal and error-related processing, suggesting that adults with ADHD may suffer from deficiencies in evaluative error-detection. In children, the difference in failed-stop N2 between ADHD and control groups has shown mixed results. Some studies have found a reduced failed stop N2 in children with ADHD (Overtoom et al., 2002; Pliszka et al., 2000), while others have not (Dimoska et al., 2003; van der Schoot et al., 2002). This opens an avenue of research into error-related processing in children and adults with ADHD.

However, to avoid the confounding effects of stop-signal processing overlap (see Study III, Chapter 6), error-related processing may be best examined time-locked to the response, rather than the stop-signal.

#### 8.7.5 *ADHD Summary*

Overall, this review suggests that response inhibition in the simple stop-signal task may be deficient in adults with ADHD, as evidenced by a slower SSRT and delayed successful stop P3. Furthermore, reduced inhibitory control may also be partly due to deficient early sensory processing of the stop-signal. Although selective inhibition has, thus far, not been examined in adults with ADHD, children with the disorder show impaired performance. However, it is unclear whether selective inhibition deficits may be more pronounced than simple inhibition deficits because a within-subject comparison is currently lacking.

An examination of response processes suggests that adults with ADHD, unlike children with the disorder, may show similar or faster responding relative to controls. Although this may partly support the notion of over-active response processing as contributing to impulsivity in adults with ADHD, electrophysiological indices of response activation have not shown any differences between adult ADHD and control groups. Finally, a reduced failed stop N2 suggests that error-related processing may be impaired in adults with ADHD relative to controls.

In response to the deficiencies in the adult ADHD literature, Chapter 10 examines inhibitory performance and associated ERPs between simple and selective versions of the stop-signal task in a group of adults with ADHD, relative to non-clinical adults.

## 8.8 Impulsivity as a Trait in ADHD: A Dimensional Account

Recently, there have been a growing number of attempts by researchers to develop an integrative model of deficient inhibition that considers the relationship between personality traits and psychopathologies (Nigg, 2000). Psychopathologies are increasingly being considered as representations of personality dimensions, rather than categories (i.e. to *have-or-not-have* a disorder), with symptoms believed to lie on a continuum, and clinically significant expressions reflecting an extreme of a personality trait (e.g. Sonuga-Barke, 1998). Impulsivity, in particular, is a good candidate trait to examine in ADHD because it constitutes one of the symptom dimensions in the diagnostic criteria. The question that this begs is: does ADHD-related impulsivity reflect an extreme form of the impulsiveness trait? If so, impulsivity may be mediated by the same mechanism in both clinical and non-clinical individuals, with differences, rather than qualitative, being one of degree.

Typically researchers use taxometric procedures, which examine the covariation among symptoms or test scores, to determine the presence of patterns that may reflect latent categories or dimensions (Haslam, 2003). However, psychometric and behavioural measures provide limited insight into individual differences. That is, similar overt behaviour may disguise underlying differences in neural processes (Bush et al., 1999; Johnstone & Barry, 1996; Karayanidis et al., 2000). For example, studies examining quantitative EEG suggest that ADHD symptomatology is associated with distinct electrophysiological patterns. One study found that adults diagnosed with ADHD showed enhanced theta activity relative to adults presenting with ADHD symptoms, but who failed to meet the diagnostic criteria for the disorder (Bresnahan & Barry, 2002). However, the latter group did not differ from controls. This supports the

distinctive quality of the impulsivity deficit in ADHD, and argues against the notion of a continuum of symptom severity (Bresnahan & Barry, 2002).

Chapter 10 examines whether a common mechanism underlies stop-signal task performance, a form of motor-related impulsivity, for the impulsiveness trait and in adults with ADHD. This is achieved through a comparison of an adult ADHD group with a non-clinical group of subjects who reported high degrees of the impulsiveness trait.

## **8.9 Introduction to Studies V and VI**

Study V (Chapter 9) examines stop-signal task performance and ERP indices of inhibition and response activation between extreme low and high impulsivity groups, as defined by Eysenck's Impulsiveness subscale (1993b). This allows an insight into the relationship between the impulsiveness trait and response inhibition. Study VI (Chapter 10) is an extension of Study V in that the low and high impulsivity groups are examined relative to a group of adults diagnosed with ADHD in simple and selective inhibition conditions. Specifically, it was expected that the presence of a response inhibition deficit in ADHD would manifest in poorer inhibitory performance and a reduced P3 component, relative to the low impulsivity group. The comparison of the ADHD and high impulsivity group was included to determine whether impulsivity in ADHD may reflect a more severe form of the impulsiveness trait, thereby, arguing for a dimensional view. Finally, the aggregate of findings in the last two studies are expected to provide further insight into the nature of the stop-signal inhibition process in impulsive populations.

## **9. Study V – The impulsiveness trait and stop-signal inhibition**

### **9.1. Abstract**

Impulsivity in non-clinical adults may be mediated by an over-active response process, a deficient inhibition process, or both. The aim of the present study was to examine stop-signal task performance and electrophysiological indices of response activation and inhibition in extreme Low ( $n = 20$ ) and High ( $n = 20$ ) impulsivity groups of non-clinical adults, as defined by Eysenck's Impulsiveness Questionnaire. At the immediately overt level of performance, groups did not differ. However, underlying processing differences were observed with the High group showing greater activity of the motor-related LRP, relative to the Low group, suggesting enhanced response activation. Furthermore, processing of the stop-signal was enhanced in the High compared to Low group, with larger N1 and P3 amplitudes for successful stop trials reflecting increased sensory and inhibitory processing, respectively. Finally, response-locked Ne and Pe both showed small tendencies towards being larger in the High than Low group, suggesting greater detection and affective processing of inhibition errors in the former group. The implications of these findings are that healthy, non-clinical adults who report high degrees of impulsivity are capable of compensating for this response style, resulting in comparable performance to individuals who report low degrees of impulsivity, by activating inhibitory processes to a greater extent.

## 9.2. Introduction

The impulsiveness personality trait, as defined by Eysenck (1993b), reflects a predisposition in individuals to act quickly in response to either internal or external stimuli, without planning the action or thinking about the possible repercussions (Moeller et al., 2001, p. 1784). It has been suggested that impulsivity may stem from a deficit in response inhibition (Logan et al., 1997), which provides the cognitive system with a vital delay so that the consequences of a particular behaviour may be evaluated prior to its execution (Barkley, 1997). Alternatively, or in addition, it has been suggested that impulsivity may be due to over-active response processes (Gray, 1987; Jouvent & Pierson, 1998).

Although a response inhibition deficit has been implicated in underlying impulsivity in clinical populations such as ADHD (e.g. Oades et al., 2002; Schachar & Logan, 1990a), the mechanisms underlying impulsiveness in high-functioning, non-clinical adults have rarely been investigated, and in the studies that do exist, results have been inconsistent. Using the stop-signal task, some adult studies have reported a significant correlation between Eysenck's Impulsiveness trait (1993b) and SSRT, but no relationship with Go RT (Logan, 1997; Gorlyn et al., 2005), while others have shown reduced inhibition probability (Marsh et al., 2002) or general stopping problems (Vigil-Colet & Codorniu-Raga, 2004) in High compared to Low impulsive groups (defined by a median-split on Impulsiveness scores). However, a number of inhibition studies have failed to find any relationship between the impulsiveness trait and performance in the stop-signal task (Cheung et al., 2004; Lijffijt et al., 2004; Rodriguez-Fornells et al., 2002), go/nogo task (Horn et al., 2003; Krijns et al., 1994) or CPT (Fallgatter & Herrmann, 2001; Harmon-Jones et al., 1997).

With respect to ERPs, there has been no evidence of an association between the inhibition-related N2 or P3 components and impulsiveness (Fallgatter & Herrmann, 2001; Harmon-Jones et al., 1997), although in oddball-type tasks, impulsive subjects who have suffered from substance abuse, aggression or depression, typically show reduced P3 amplitude (Barratt et al., 1997; Fallgatter et al., 1998; Gerbing et al., 1987; Gerstle et al., 1998; Jouvent & Pierson, 1998; Mathias & Stanford, 1999). In contrast, brain imaging studies show an increase, rather than decrease, in specific areas of inhibition-related frontal regions with an increase in impulsiveness when successfully stopping a response (Horn et al., 2003). Furthermore, indices of response activation also show inconsistent effects, with some findings suggesting that impulsive behaviour may be due to an over-active response process (Krijns et al., 1994), while others show no relationship (Brown et al., 1989). Therefore, the role of response inhibition and activation processes in the impulsiveness trait are unclear.

As a result of the PCA-derived findings in Chapter 7, which suggested that a slow-wave (SW) component contributed to the differences between stop-signal probability conditions, the present study examined the role of SW activity in underlying the impulsiveness trait. Because of the long latency of the component, it is generally quantified as the mean of activity in the latter part of the epoch, approximately 400 – 700 ms after the onset of the stimulus (Pritchard, Brandt, & Barratt, 1986). Pritchard et al. (1986) found that this interval corresponded well with SW factor scores derived from a PCA. However, Johnstone, Barry, and Dimoska (2003) found that dissociating the SW from the average ERP through frequency-specific filtering, focussing on the 0.01 to 2 Hz delta band, allowed identification of more specific ADHD vs. control differences than would have been found through conventional SW mean amplitude quantification. Therefore, both methods are employed in the present study. In previous studies, Krijns

et al. (1994) found that a negative SW (NSW) was enhanced to a greater extent in the right than left hemisphere in highly impulsive subjects, compared to those who showed low degrees of impulsiveness. Furthermore, when subjects were divided using the sensation-seeking trait, a reduced positive SW (PSW) and increased NSW activity were found for high sensation seekers (Krijns et al., 1994), which may be interpreted to reflect decreased inhibitory control and an increased preparedness to respond (Birbaumer et al., 1990; Rockstroh et al., 1992). In contrast, Barratt (1987) found no relationship between a PCA-extracted SW factor and impulsiveness, as measured by BIS (Barratt, 1959). These findings suggest it may be worthwhile examining differences in SW components between Low and High impulsivity groups.

The aim of the current study was to examine differences in stop-signal task performance and ERP indices of response inhibition and activation between two extreme groups (Low versus High) on Eysenck's (IVE) Impulsiveness subscale (1993b). It was expected that subjects in the High group would perform more impulsively in the stop-signal task, relative to the Low group, manifesting as (a) a longer SSRT, (b) reduced inhibition probability, and (c) a flatter inhibition function. If impulsive performance is due to deficient response inhibition, this should be reflected in a reduced and/or delayed successful stop P3 in the High compared to Low group. Alternatively, if impulsivity is the result of over-active response processing, the High group may show larger LRP amplitude, relative to the Low group. In contrast, subjects in the Low group are expected to adopt a cautious response style and may use a more deliberate response selection process, as reflected in successful stop N2. SW components were examined to determine differences in general neuronal excitation and inhibition. Finally, response-locked ERPs were also examined to determine the effect of the impulsiveness trait on error-detection and evaluation processes.



### 9.3 Method

#### 9.3.1 Subjects

Forty adults (31 female) aged 18 years 9 months to 30 years 0 months (mean = 20.8 years, SD = 2.4 years) were selected after preliminary testing conducted using the IVE Questionnaire (Eysenck, 1993b) from a group of 200 undergraduate psychology students who completed the scale as a means of partially satisfying requirements in a subject. Students who obtained a score on the Impulsiveness subscale placing them in the top or bottom 15 % of scorers comprised the subjects for this study. Of these, two equal groups of 20 were created for the *High* (5 males) and *Low* (4 females) impulsivity groups. Subjects were included if they had obtained a standardised score of 80 or greater on the RPM (Raven, 2000), and if they had never suffered an epileptic seizure, serious head injury, period of unconsciousness or any psychiatric condition. The General Health Questionnaire-28 (GHQ-28; see section 9.3.4.1 for details) was used to screen for current symptoms, anxiety and insomnia, social dysfunction, and severe depression, which may have been experienced in the short-term (Goldberg & Hillier, 1979). Subjects who received a score greater than 4 on the anxiety and depression subscales were excluded from the study. Each subject reported no problems with hearing, had normal or corrected-to-normal vision and were native English speakers. Informed consent was obtained from all subjects after the testing equipment had been explained, with the option to withdraw without penalty.

#### 9.3.3 Procedure

The experimental session began by completing the IVE (Eysenck & Eysenck, 1975), the Frontal Systems Behaviour Self-Rating Scale (FrSBe), the GHQ-28

(Goldberg & Hillier, 1979), the RPM (Raven, 2000) and an information sheet used to screen for stimulant use, handedness and history of health concerns, and a consent form. In the laboratory, all procedural details and specifications for the stop-signal task are as outlined in Study II (Chapter 5), except for the fact that subjects were asked to respond with Digit II of the left and right hands. That is, all subjects completed the simple and selective conditions of the stop-signal task. There were 12 subjects in the low group and 10 subjects in the high group that received the simple condition first. However, due to a lack of meaningful statistically significant Group x Condition effects,<sup>38</sup> only findings for the simple condition are presented here.

#### *9.3.4 Psychometric Measures*

##### **9.3.4.1 General Health Questionnaire – 28 Items (GHQ-28)**

The GHQ-28 is a self-report questionnaire designed for detecting individuals with a diagnosable psychiatric disorder (Goldberg & Hillier, 1979). It consists of four subscales that measure the severity of current somatic symptoms, anxiety and insomnia, social dysfunction, and severe depression. Furthermore, a total score is calculated as the aggregate of the four subscales. It has been recommended that the “GHQ scoring method” of (0-0-1-1) be used for scoring items on the 4-point scale (Goldberg & Hillier, 1979) when the test is used for screening purposes. Using a threshold score of 4/5 (i.e. below threshold includes scores 0-4; above threshold includes scores 5+) results in the correct identification of 88.0 % of true positives (Goldberg & Hillier, 1979).

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<sup>38</sup> See Study II (Chapter 5) for a comparative investigation of simple vs. selective inhibition in non-clinical adults.

### 9.3.4.2 Eysenck's Impulsiveness (IVE) Questionnaire

The IVE contains Impulsiveness, Venturesomeness and Empathy subscales and is comprised of 54 items (see also section 8.3.1) (Eysenck, 1993b). Eysenck (1985) derived norms for the IVE questionnaire from a large sample of English adults aged 16 – 87 years. These are shown in Table 9.1 (adapted from Eysenck et al., 1985).

**Table 9.1. Means (*M*) and standard deviations (*SD*) of the IVE subscales for males and females. Adapted from Eysenck et al. (1985).**

IVE Subscales	Males (n = 383)		Females (n = 206)	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Impulsiveness	8.76	4.31	8.17	4.44
Venturesomeness	10.61	3.22	8.32	3.83
Empathy	11.22	3.51	14.3	3.12

### 9.3.4.3 Frontal Systems Behaviour Self-rating Scale (FrSBe)

The FrSBe (Psychological Assessment Resources, Inc., Florida, USA) is a self-rating questionnaire that was developed to assess the severity of behavioural syndromes related to three frontal-subcortical circuits. The Apathy subscale (14 items) quantifies problems related to the mesial ACC circuit, including motivational disturbances such as apathy and akinesia. The Disinhibition subscale (15 items) is related to the orbitofrontal circuit and measures emotional lability and disinhibited behaviour. The Executive Dysfunction subscale (17 items) quantifies problems associated with the dorsolateral prefrontal circuit such as planning, self-regulation, sequencing of behaviour, and flexibility of thinking (see section 1.3) (Stout, Wyman, Johnson, Peavy, & Salmon, 2003). Finally, the Overall Frontal Systems subscale reflects the severity of overall frontal-related dysfunctions and is calculated as the aggregate score of the three other subscales. The FrSBe provides a measure of behavioural change over time, including

both baseline (retrospective) and current assessments of behaviour. Only the current assessment was used in the present study. Each item is rated on a 5-point Likert scale and the questionnaire can be administered in 15 minutes.

### 9.3.5 *Electrophysiological Recording*

All details for the recording of ERPs in this study are as outlined in Study I (Chapter 4). In brief, EEG was recorded from 17 sites of the International 10-20 system.

The stimulus-locked ERP epoch was defined as 200 ms pre- to 800 ms post-stop-signal onset and ERP averages were computed for successful (mean number of epochs = 34.5, SD = 15.7) and failed stop trials (mean number of epochs = 34.5, SD = 15.7). The response-locked ERP epoch was defined as 500 ms pre- to 500 ms post-overt response onset, with ERP averages computed for failed stop and correct ignore-signal trials. Response-locked difference waveforms were subsequently computed with ignore-signal trials subtracted from failed stop trials (mean number of epochs = 34.5, SD = 15.7).

Refer to section 7.3.5.2 for details on procedure used to calculate the LRP and score LRP-related measures.

### 9.3.6 *Data Analysis*

All performance measures are outlined in Study II (Chapter 5). ANOVAs were used to analyse performance measures with “Group” (Low vs. High) as a between-subjects factor. Analysis of the inhibition function included “Delay” as an additional

within-subjects factor. Planned contrasts compared data from (MRT – 0) through to (MRT – 450) ms examining polynomial contrasts.<sup>39</sup>

Grand average ERP waveforms were displayed for the purpose of defining each component. The peak amplitude for each component was quantified within a predetermined latency window by means of an automatic peak-picking program, using Scan software (Neuroscan, v4.3), with the latency for each component fixed across all sites to the peak latency of the site of maximum amplitude (Pailing & Segalowitz, 2004; Picton et al., 2000; Spencer et al., 2001). Stimulus-locked ERP waveforms showed a large N1/P3 complex for all ERP averages, while an additional smaller P2/N2 complex occurred in some subjects. Peak amplitudes were quantified for the N1 (80 to 190 ms, locked at Cz) and P3 (260 to 450 ms, locked at Cz) components as the maximum points in the large negative-positive complex, relative to the 200 ms pre-stimulus baseline period. Mean amplitude was quantified in the 200 to 250 ms latency range. As a result of the finding in Study IV (Chapter 7), whereby the auditory-evoked N2 was found to be overlapped by the P3 in the centro-parietal region, analyses of N2 were restricted to the frontal sites (F3, Fz and F4).<sup>40</sup> Grand average response-locked ERP waveforms allowed identification of Ne (0 – 150 ms) and Pe (250 – 550 ms), with peak amplitude measured relative to a 200 ms pre-response baseline (Bernstein et al., 1995b).

In Study IV (Chapter 7), the PCA showed a SW factor that appeared to account for a large portion of the variability in amplitude between low and high probability conditions. Therefore, the SW component was quantified in the present study using two methods: (1) the traditional method of mean amplitude in the 400 – 700 ms latency

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<sup>39</sup> As there were 5 subjects who did not receive stop-signals at the (MRT-600) ms delay, this variable was excluded from the inhibition function analysis.

<sup>40</sup> Analysis of N2 amplitude was also performed including the Sagittal factor, however, results were very similar to that found for P3 amplitude, indicating component overlap.

range of the original ERP averages (0.01 to 30 Hz) (termed mean slow-wave activity; MSW) (Pritchard et al., 1986), and (2) by filtering the stop-signal ERP averages for successful and failed trials with a low-pass filter (0.01-2 Hz, down 48 dB), in line with Johnstone and Barry (1999). In the low-pass filtered SW activity, grand average ERP waveforms were displayed for the purpose of identifying the negative and positive components. The waveform contained an early negative (NSW) and a late positive (PSW) component. NSW was quantified as the most negative peak in the -100 to 300 ms latency range and PSW was quantified as the most positive peak in the 300 to 800 ms latency range, relative to the pre-stimulus period (i.e. -200 to -100 ms).

Statistical analyses of the topography of ERP component amplitude was as outlined in previous studies and included data collected from nine sites (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4). Furthermore, a between-subjects factor “Group” compared the Low and High impulsive groups. Unless otherwise indicated, degrees of freedom for all statistical effects reported are (1, 38).

## 9.4 Results

### 9.4.1 Psychometric Measures

Firstly, low (mean age = 21.5 years, SD = 2.8 years) and high (mean age = 20.2 years, SD = 1.8 years) groups did not differ in age ( $F = 3.0$ ,  $p > .05$ ). Table 9.2 provides the summary statistics for the psychometric measures in the Low and High impulsivity groups. For the IVE, the High group obtained larger scores on the Impulsiveness and Venturesomeness, but not Empathy, subscales. Average Impulsiveness scores in the High and Low groups were approximately 1.5 SDs above and below the norm values (see Table 9.1; across gender), respectively. For the FrSBe,

the High group reported significantly greater problems with Disinhibition, Executive Dysfunction and Overall Frontal Systems problems, compared to the Low group. The groups did not differ on the Apathy subscale.

**Table 9.2. Means, standard deviations (in brackets) and statistical effects for the psychometric measures in the Low and High impulsivity groups.**

<b>Psychometric</b>	<b>Low</b>	<b>High</b>	<b><i>F</i></b>	<b><i>p</i></b>
<b>IVE</b>				
<b>Impulsiveness</b>	1.8 (1.0)	15.2 (1.3)	1353.8	.000
<b>Venturesomeness</b>	7.3 (2.6)	10.9 (4.1)	11.0	.002
<b>Empathy</b>	15.0 (2.9)	13.4 (3.3)	2.5	.122
<b>FrSBe</b>				
<b>Apathy</b>	60.9 (13.3)	61.7 (14.9)	.032	.859
<b>Disinhibition</b>	50.9 (9.4)	73.4 (18.5)	23.7	.000
<b>Executive Dysfunction</b>	52.2 (8.3)	68.3 (11.4)	26.1	.000
<b>Overall Frontal Systems</b>	55.4 (10.9)	72.1 (13.4)	19.0	.000

Correlations between psychometric measures (see Table 9.3) revealed that within the IVE, the Impulsiveness subscale correlated positively with Venturesomeness, however, Empathy did not correlate with either scale. Within the FrSBe, Apathy and Disinhibition correlated positively with both the Executive Dysfunction and the Overall Frontal Systems subscales, although the former two did not correlate with each other, while the latter two did. Between scales, IVE Impulsiveness correlated positively with the Disinhibition, Executive Dysfunction and Overall Frontal Systems subscales of the FrSBe, while Venturesomeness and Empathy both showed positive relationships with Disinhibition only.

**Table 9.3. Correlations between psychometric measures across the sample (N = 40).**

Psychometric	I	V	E	Apathy	Dis	Executive Dys	Overall FS
<b>IVE</b>							
Impulsiveness	1	.483**	-.225	.091	.612**	.659**	.601**
Venturesomeness	.483**	1	-.310	-.095	.376*	.290	.281
Empathy	-.225	-.310	1	-.019	-.400*	-.301	-.291
<b>FrSBe</b>							
Apathy	.091	-.095	-.019	1	.156	.466**	.537**
Disinhibition	.612**	.376-	-.400*	.156	1	.778**	.866**
Executive Dys	.659**	.290	-.301	.466**	.778**	1	.943**
Overall FS	.601**	.281	-.291	.537**	.866**	.943**	1

Notes: \*\* Correlation is significant at the 0.01 level (2-tailed); \* Correlation is significant at the 0.05 level (2-tailed); Dis = Disinhibition; Dys = Dysfunction; FS = Frontal Systems.

#### 9.4.2 Performance Measures

Table 9.4 provides the means and effect summaries for the performance measures. The groups did not differ on any performance measure. Although SSRT appeared to be longer in the High compared to Low group, this difference was not significant. Across groups, MRT for failed stop trials was shorter compared to no-signal trials ( $F = 205.5, p < .001$ ).

**Table 9.4. Means, standard deviations (in brackets), and statistical effects for the performance measures.**

	Low	High	<i>F</i>	<i>p</i>
Go MRT (ms)	591.4 (168.6)	572.3 (133.9)	0.16	.693
Omission Errors (%)	1.3 (2.1)	0.6 (0.6)	2.0	.163
Choice Errors (%)	6.6 (1.7)	7.0 (2.7)	0.35	.557
SSRT (ms)	249.5 (94.6)	277.6 (138.7)	0.6	.460
FSRT (ms)	179.6 (58.7)	163.5 (63.0)	0.70	.407

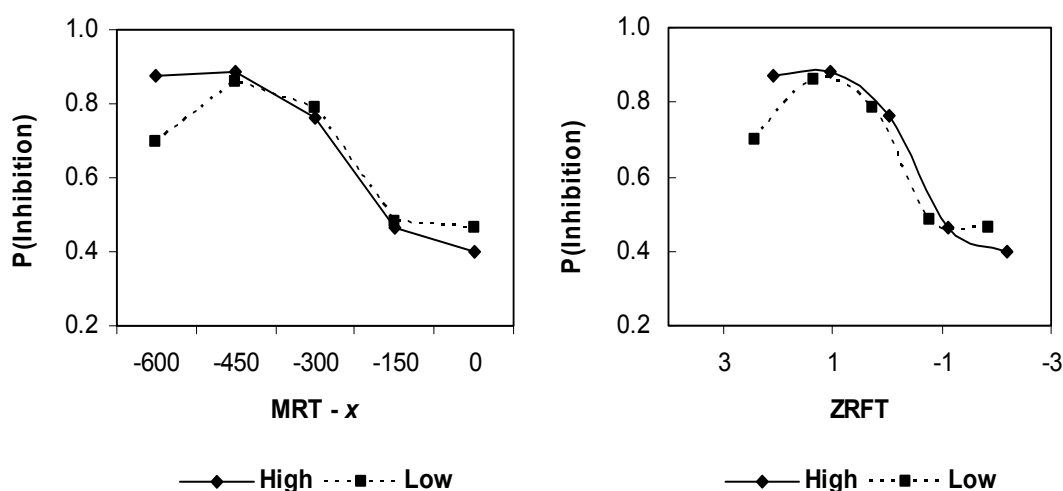
Notes: Go MRT = Primary task mean reaction time to go stimuli on no-signal trials; SSRT = Mean stop-signal reaction time; FSRT = Mean reaction time to go stimuli on failed inhibition trials.

Figure 9.1 shows the inhibition functions for each condition plotted by stop-signal delay (left panel) and ZRFT (right panel). Inhibition probability showed a linear effect between stop-signal delays ( $F = 109.8, p < .001$ ), which did not differ between



groups ( $F < 1$ ). Across the stop-signal delays, average inhibition probability did not differ between groups ( $F = 1.3, p = .262$ ). Plotting inhibition probability as a function of ZRFT did not align the inhibition functions any further (see Figure 9.1, right panel).

Correlations were performed between the psychometric and performance measures. The only significant relationships occurred for SSRT with the Executive Dysfunction subscale ( $r = .40, p < .05$ ) and with Overall Frontal Systems subscale of the FrSBe ( $r = .36, p < .05$ ).



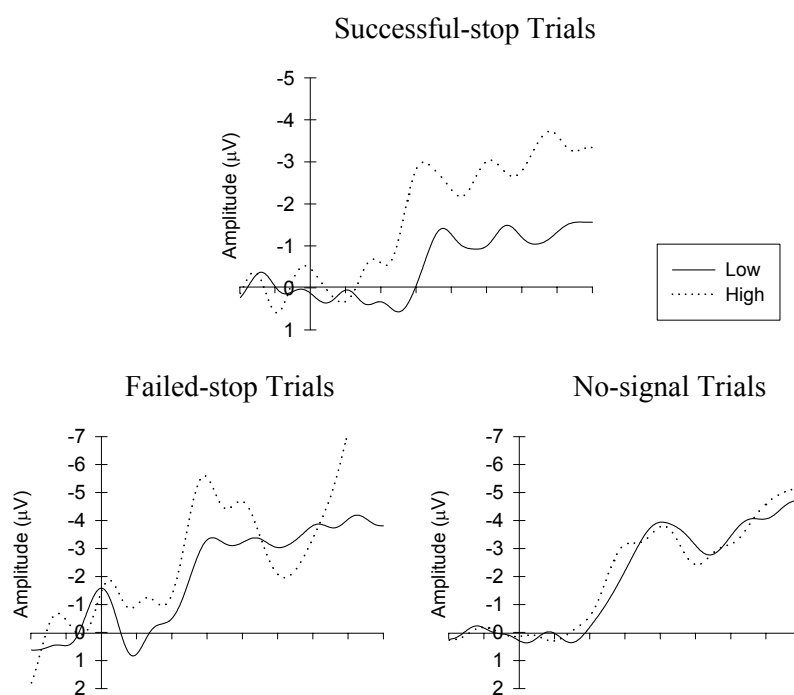
**Figure 9.1.** Inhibition probability as a function of stop-signal delay (MRT – x) (left panel) and as a function of ZRFT (right panel). Note: (1) 5 subjects in the Low group and 5 subjects in the High group did not receive a stop-signal at the (MRT – 600) ms delay (i.e.  $n = 15$ ), and (2) statistical effects exclude this delay.

#### 9.4.3 Lateralised Readiness Potential (LRP)

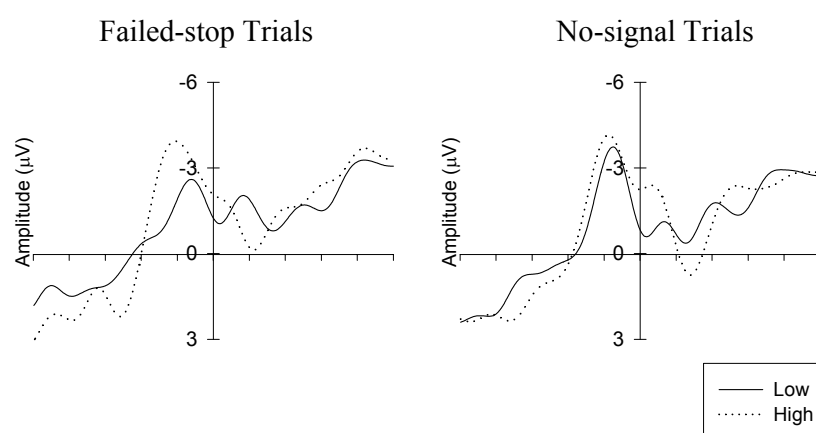
Across Group, stimulus-locked LRP (sLRP) amplitude was larger for failed stop compared to no-signal trials ( $F = 23.2, p < .001$ ), and for successful stop compared to response trials (i.e. the mean of failed stop and no-signal trials;  $F = 31.4, p < .001$ ). Across Trial, sLRP amplitude was larger in the High compared to Low group ( $F = 58, p < .05$ ), however, an interaction with Trial revealed that this difference occurred for

failed stop but not no-signal trials ( $F = 4.5, p < .05$ ). Although Figure 9.2 suggests that the onset of the sLRP was later in the Low group, particularly for successful stop trials, this difference was not statistically significant ( $F = 2.0, p = .168$ ).

With respect to the response-locked LRP, its amplitude was larger ( $F = 4.5, p < .05$ ), and the onset-to-peak interval was longer, for failed stop compared to no-signal trials across groups ( $F = 9.6, p < .01$ ; see Figure 9.3). There were no between-group differences for any response-locked LRP measures.



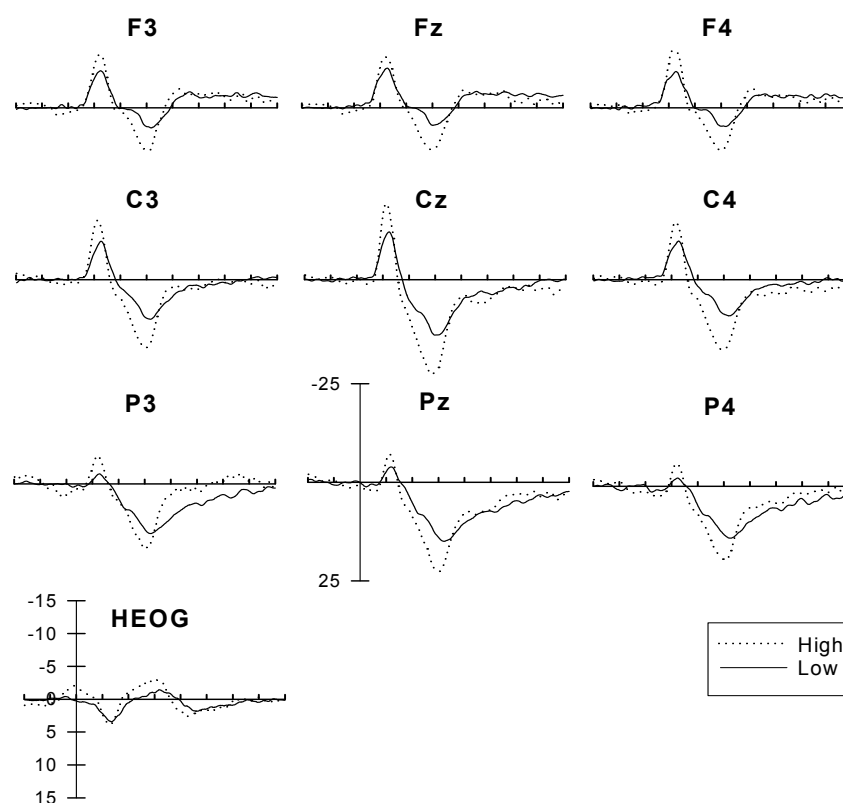
**Figure 9.2.** Average stimulus-locked lateralised readiness potential waveforms in the Low and High groups for successful stop, failed stop and no-signal trials. Notes: for this and subsequent figures, (1) x-axis marks every 100 ms, (2) vertical bar indicates go stimulus onset, (3) negative-going amplitude is up.



**Figure 9.3. Average response-locked lateralised readiness potential waveforms in the Low and High groups for failed stop and no-signal trials.**

#### 9.4.4 Stimulus-locked ERPs: Successful Stop Trials

Figure 9.4 depicts the average ERP waveforms for successful stop trials in the Low and High groups. In the Low group, components identified included the N1, which was most evident in the fronto-central region (136.9 ms), a small N2 (234.0 ms) in the frontal region and a centro-parietal P3 (316.6 ms). In the High group, the grand average waveforms show a large N1/P3 complex (N1 = 136.9 ms; P3 = 291.1 ms). The N2 was not evident in the grand average waveforms of the High group, and was not evident for most individual subjects. For the Low group, a small P2/N2 complex is apparent (N2 = 206.1 ms). The SW component (400 – 700 ms) was more negative in the frontal region, and positive in the centro-parietal region, although amplitude did not appear to differ between groups. Note that horizontal eye movement (HEOG) was relatively minimal for successful stop trials across groups, supporting the validity of the LRP measurement for these trials.



**Figure 9.4.** Average ERP waveforms at nine sites and the horizontal eye movement channel (HEOG) for successful stop trials in the Low and High groups. Notes: (1)  $x$ -axis ticks = 100 ms, (2) stimulus onset indicated by vertical bar at Pz, (3)  $y$ -axis =  $\pm 25 \mu\text{V}$ , (4) HEOG  $y$ -axis =  $\pm 15 \mu\text{V}$ , (5) negative-going amplitude is up.

#### 9.4.4.1 Component Analysis

See Table 9.5 for means and effect summaries. For successful stop trials, N1 showed midline, fronto-central maximas, with the midline > lateral effect largest in the central region. Furthermore, a left > right effect was found for N1 amplitude in the frontal region, with the opposite effect in the parietal region. Mean N2 amplitude in the frontal region did not differ across the lateral sites. P3 showed midline-right, centro-parietal maximas, with the midline > lateral effect largest in the centro-parietal region. MSW was more positive in the right-midline, centro-parietal regions, with the right > left effect largest in the parietal region.

Between groups, N1 for successful stop trials was larger in the High compared to Low group, with the largest difference at the vertex. N2 mean amplitude did not differ between groups. P3 amplitude was larger in the High compared to Low group, with the largest difference in the central region. MSW amplitude was more positive in the right > left region in the Low group, with this effect reduced in the High group. With respect to latency, P3 showed a tendency of peaking earlier in the High compared to Low group.

**Table 9.5. A summary of ERP component amplitude and latency means and statistical effects for successful stop trials. Notes: (1) all values are in  $\mu\text{V}$ .**

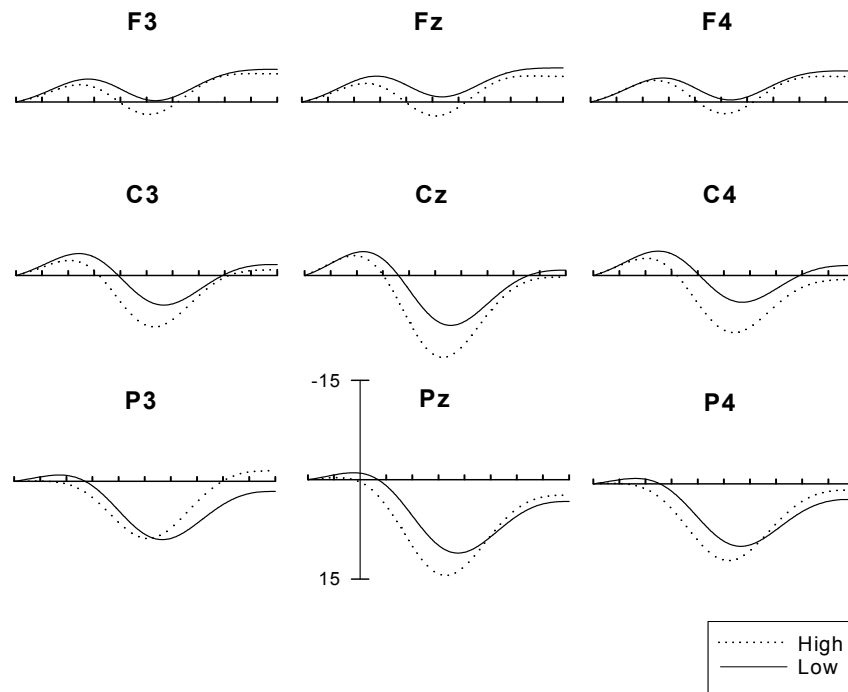
Effect		Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>Amplitude</b>					
<b>N1</b>	Lat	M vs. L/R	-12.9 vs. -11.4	13.3	.001
	Sag	f vs. p	-13.8 vs. -6.0	59.9	.000
		c vs. f/p	-15.9 vs. -9.9	112.3	.000
	Lat x Sag	fL to fR vs. pL to pR	-13.5 to -14.3 vs. -6.2 to -5.4	5.2	.029
		cM to cL/R vs. f/pM to f/pL/R	-18.6 to -14.5 vs. -10.1 to -9.8	41.8	.000
	Group	Low vs. High	-10.2 vs. -13.6	6.2	.015
	Group x Sag x Lat	cM to cL/R vs. f/pM to f/pL/R	Low: -15.9 to -12.8 vs. -9.0 to -8.2 High: -21.3 to -16.2 vs. -11.1 to -11.6	7.5	.009
<b>N2</b>	No effects				
<b>P3</b>	Lat	L vs. R	13.9 vs. 14.9	5.3	.027
		M vs. L/R	-12.9 vs. -11.4	36.1	.000
	Sag	f vs. p	10.5 vs. 18.0	29.8	.000
		c vs. f/p	18.5 vs. 14.3	66.0	.000
	Lat x Sag	fM to fL/R vs. pM to pL/R	10.4 to 10.5 vs. 21.0 to 16.5	17.4	.000
		cM to cL/R vs. f/pM to f/pL/R	23.3 to 16.2 vs. 15.7 to 13.5	41.8	.000
	Group	Low vs. High	13.2 vs. 18.1 Low: 15.3 vs. 12.2 High: 21.7 vs. 16.4	11.0	.002
	Group x Sag	c vs. f/p		4.1	.050
<b>MSW</b>	Lat	L vs. R	0.08 vs. 1.1	8.1	.007
		M vs. L/R	1.8 vs. 0.6	4.4	.042
	Sag	f vs. p	-3.0 vs. 3.8	34.9	.000
		c vs. f/p	2.1 vs. 0.4	5.9	.020
	Lat x Sag	fL to fR vs. pL to pR	-3.1 to -2.8 vs. 2.1 to 3.9 Low: -3.1 vs. 5.0 High: -2.9 vs. 2.7	4.8	.035
	Group x Lat	L vs. R		5.3	.027
<b>Latency</b>					
<b>P3</b>	Group	Low vs. High	316.6 vs. 291.1	3.9	.056

Note: Abbreviations shown on next page.

Abbreviations: vs. = versus; C = condition; Lat: Lateral; S: Sagittal; L = left; R = right; M = midline; L/R = mean of the left and right regions; f = frontal; c = central; p = parietal; f/p = mean of the frontal and parietal regions; fL = F3; fR = F4; fM = Fz; fL/R = mean of F3 and F4; cL = C3; cR = C4; cM = Cz; cL/R = mean of C3 and C4; pL = P3; pR = P4; pM = Pz; pL/R = mean of P3 and P4; f/pL = mean of F3 and P3; f/pR = mean of F4 and P4; f/pM = mean of Fz and Pz; f/pL/R = mean of F3, F4, P3 and P4.

#### 9.4.4.2 Event-related Slow-wave Components (0.01 to 2 Hz)

Figure 9.5 depicts the grand average ERP waveforms for the slow-wave (0.01 to 2 Hz) band in the low and high groups.



**Figure 9.5.** Average event-related slow-wave ERP waveforms (0.01 – 2 Hz) for successful stop trials in the Low and High groups. Notes: (1) x-axis ticks = 100 ms, (2) stimulus onset indicated by vertical bar at Pz, (3) y-axis =  $\pm 15 \mu\text{V}$ , (4) negative-going amplitude is up.

See Table 9.6 for means and effect summaries. Across groups, NSW showed midline, fronto-central maximas, with a right > left effect in the frontal region and the opposite effect in the parietal region. PSW showed midline, centro-parietal maximas, with a midline > lateral effect that was largest in the centro-parietal region. Between groups, while NSW amplitude did not differ, PSW showed a tendency towards being

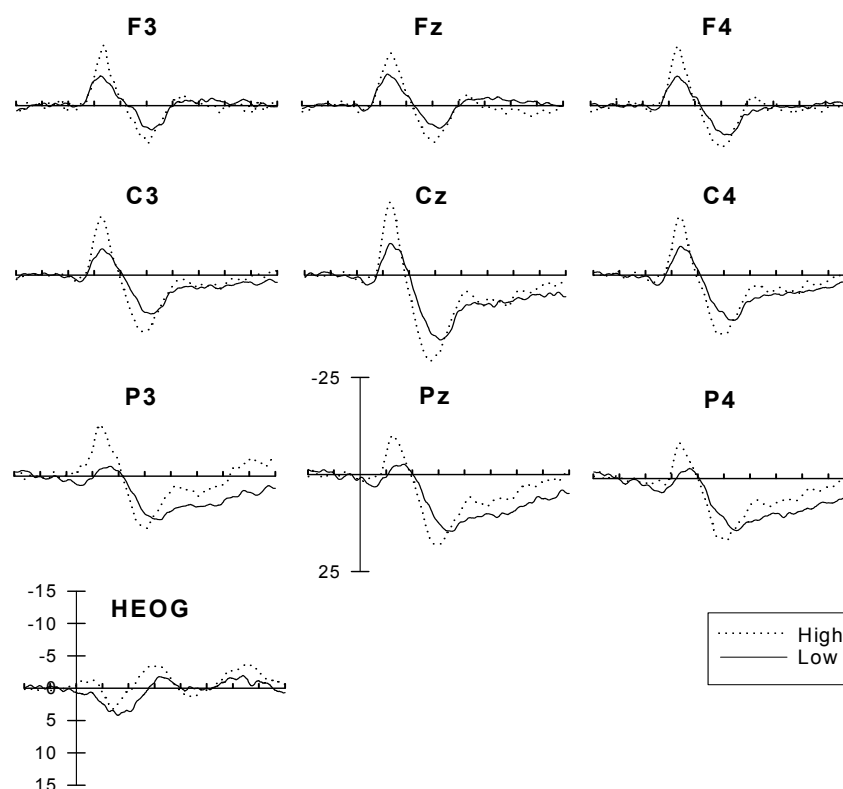
larger in the High compared to Low group, although this difference was not localised to any region (see Figure 9.5). With respect to latency, NSW peaked earlier in the High group.

**Table 9.6. A summary of event-related slow-wave component amplitude and latency means and statistical effects for successful stop trials. Notes: (1) all values are in  $\mu\text{V}$ .**

Effect		Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>Amplitude</b>					
NSW	Lat	M vs. L/R	-3.3 vs. -3.1	4.4	.042
	Sag	f vs. p	-4.1 vs. -1.1	26.6	.000
		c vs. f/p	-4.2 vs. -2.6	61.5	.000
	Sag x Lat	fL to fR vs. pL to pR	-3.9 to -4.3 vs. -1.2 to -0.8	4.7	.036
PSW	Lat	M vs. L/R	8.6 vs. 6.2	21.6	.000
	Sag	f vs. p	1.5 vs. 11.1	44.7	.000
		c vs. f/p	8.4 vs. 6.3	14.7	.000
	Lat x Sag	fM to fL/R vs. pM to pL/R	1.4 to 1.6 vs. 13.3 to 9.9	11.9	.001
		cM to cL/R vs. f/pM to f/pL/R	11.1 to 7.1 vs. 7.4 to 5.8	12.6	.001
	Group	Low vs. High	5.8 vs. 8.2	3.4	.071
<b>Latency</b>					
NSW	Group	Low vs. High	34.4 vs. -19.5 ms	5.5	.024
<b>PSW No effects</b>					

#### 9.4.5 Stimulus-locked ERPs: Failed Stop Trials

Figure 9.6 depicts the average ERP waveforms for failed stop trials in the Low and High groups. In the Low group, components identified included a fronto-central N1 (147.4 ms) and a central P3 (318.3 ms). In the High group, the grand average waveforms show a large N1/P3 complex (N1 = 128.4 ms; P3 = 291.0 ms). The N2 was not evident in the grand average waveforms for either group, with N1 and N2 appearing to merge into one broad negativity. The slow-wave component had a negative polarity in the frontal region and positive polarity in the centro-parietal region. Note that horizontal eye movement was relatively minimal for failed stop trials across groups, supporting the validity of the LRP measurement for these trials.



**Figure 9.6.** Average ERP waveforms at nine sites and the horizontal eye movement channel (HEOG) for failed stop trials in the Low and High groups. Notes: (1)  $x$ -axis ticks = 100 ms, (2) stimulus onset indicated by vertical bar at Pz, (3)  $y$ -axis =  $\pm 25 \mu\text{V}$ , (4) HEOG  $y$ -axis =  $\pm 15 \mu\text{V}$ , (5) negative-going amplitude is up.

#### 9.4.5.1 Component Analysis

See Table 9.6 for means and effect summaries. For failed stop trials, N1 showed midline, fronto-central maximas, with the midline > lateral effect largest in the central region, and a left > right effect largest in the parietal region. N2 mean amplitude showed a left-midline maximum in the frontal region. P3 showed right-midline, centro-parietal maximas, with the midline > lateral effect also largest in the centro-parietal region. MSW showed right-midline, centro-parietal maximas, with the midline > lateral effect largest in the centro-parietal region.



Between groups, N1 for failed stop trials was larger in the High compared to Low group, although the difference was not localised to any particular region. N2, P3 and MSW amplitudes did not show any significant between-group differences.

With respect to latency, N1 and P3 peaked earlier in the High compared to Low group.

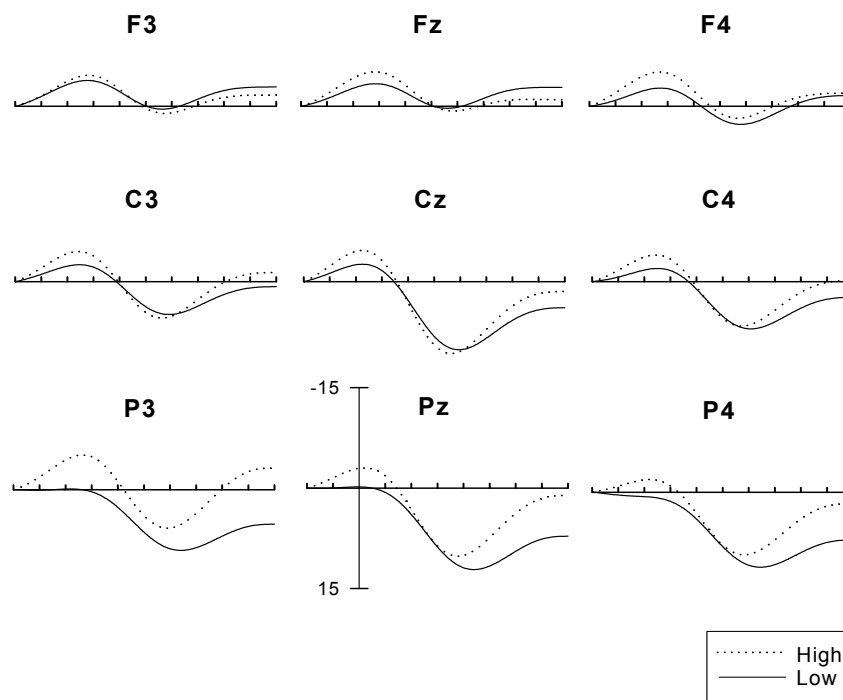
**Table 9.7. A summary of ERP component amplitude means and statistical effects for failed stop trials. Notes: (1) all values are in  $\mu\text{V}$ .**

For named stop trials. Notes: (1) all values are in $\mu V$ .					
Effect		Contrast	Effect Details	<i>F</i>	<i>p</i>
Amplitude					
N1	Lat	M vs. L/R	-14.0 vs. -13.8	12.0	.001
	Sag	f vs. p	-14.2 vs. -9.4	16.8	.000
	Sag	c vs. f/p	-16.1 vs. -11.8	75.5	.000
	Lat x Sag	fL to fR vs. pL to pR	-14.4 to -14.6 vs. -10.5 to -8.1	5.8	.021
		cM to cL/R vs. f/pM to f/pL/R	-18.9 to -14.7 vs. -11.6 to -11.9	34.7	.000
	Group	Low vs. High	-10.2 vs. -16.3	4.9	.033
N2	Lat	L vs. R	-1.1 vs. -0.09	5.5	.025
		M vs. L/R	-3.1 vs. -0.6	7.9	.008
P3	Lat	L vs. R	14.5 vs. 16.4	7.4	.010
		M vs. L/R	19.5 vs. 15.5	72.3	.000
	Sag	f vs. p	12.1 vs. 17.9	19.4	.000
		c vs. f/p	20.4 vs. 15.0	89.3	.000
	Lat x Sag	fM to fL/R vs. pM to pL/R	12.0 to 12.2 vs. 20.3 to 16.7	12.9	.001
		cM to cL/R vs. f/pM to f/pL/R	26.2 to 17.6 vs. 16.2 to 14.4	102.0	.000
MSW	Lat	L vs. R	2.2 vs. 3.9	10.6	.002
		M vs. L/R	4.5 vs. 3.1	32.6	.000
	Sag	f vs. p	-0.2 vs. 6.4	24.9	.000
		c vs. f/p	4.4 vs. 3.1	14.6	.000
	Lat x Sag	fM to fL/R vs. pM to pL/R	-0.4 to -0.1 vs. 7.6 to 5.7	12.7	.001
		cM to cL/R vs. f/pM to f/pL/R	6.4 to 3.4 vs. 3.6 to 2.8	16.4	.000
Latency					
N1	Group	Low vs. High	147.4 vs. 128.4 ms	4.7	.036
P3	Group	Low vs. High	318.3 vs. 291.0 ms	3.5	.069

#### 9.4.5.2 Event-related Slow-wave Components (0.01 to 2 Hz)

Figure 9.7 depicts the grand average ERP waveforms for the slow-wave (0.01 to 2 Hz) band in the low and high groups. See Table 9.8 for means and effect summaries. NSW showed left-midline, central maximas, with the midline > lateral effect largest in

the central region. PSW showed midline-right, centro-parietal maximas, with the midline > lateral effect was largest in the centro-parietal region. Neither component differed between groups in amplitude or latency.



**Figure 9.7.** Average event-related slow-wave ERP waveforms (0.01 to 2 Hz) for failed stop trials in the Low and High groups. Notes: (1) *x*-axis ticks = 100 ms, (2) stimulus onset indicated by vertical bar at Pz, (3) *y*-axis =  $\pm 15 \mu\text{V}$ , (3) negative-going amplitude is up.

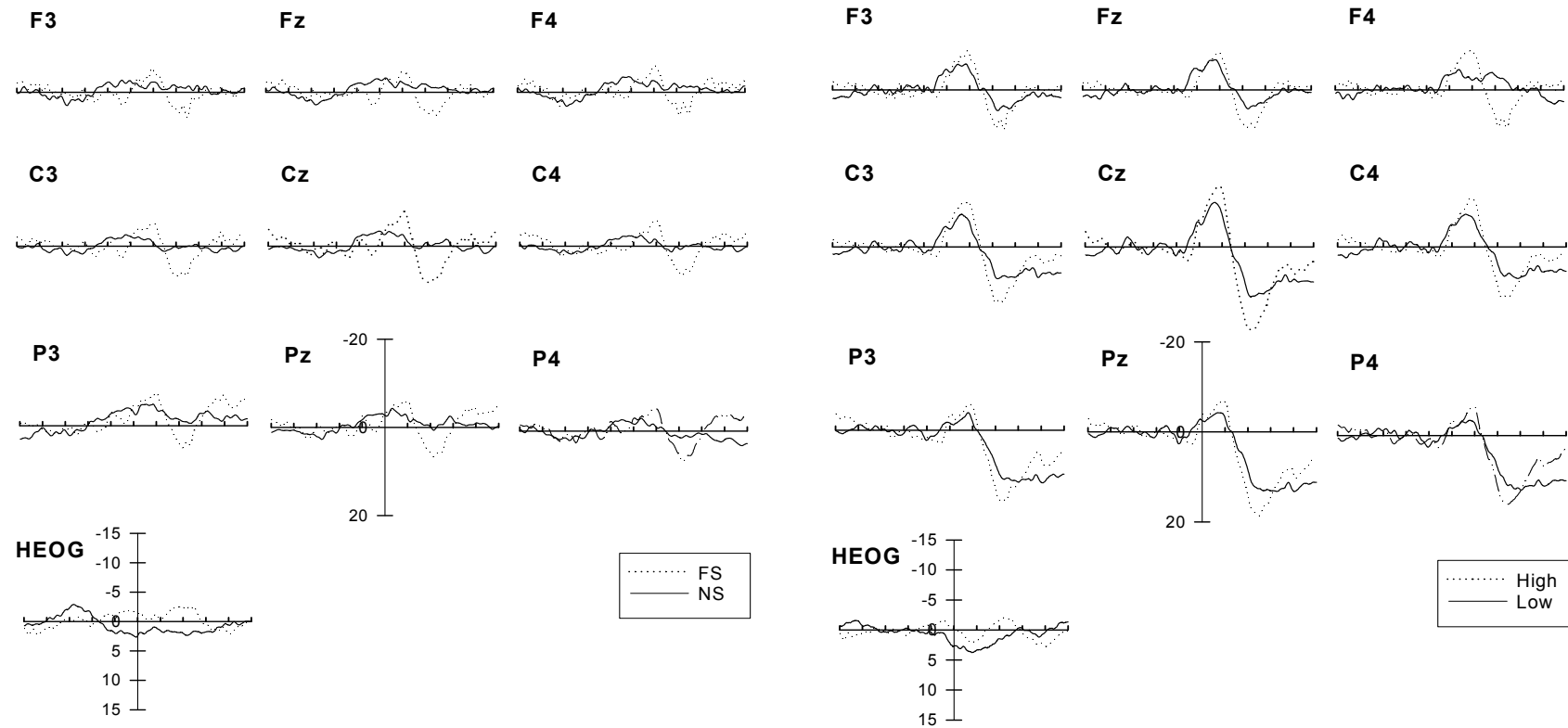
**Table 9.8.** A summary of ERP component amplitude means and statistical effects for failed stop trials. Notes: (1) all values are in  $\mu\text{V}$ .

Effect	Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>Amplitude</b>				
NSW Lat	L vs. R	-4.3 vs. -3.4	7.8	.008
	M vs. L/R	-4.3 vs. -3.9	7.3	.010
	Sag	c vs. f/p	12.3	.001
	Sag x Lat	cM to cL/R vs. f/pM to f/pL/R	10.3	.003
PSW Lat	L vs. R	5.6 vs. 7.6	12.9	.001
	M vs. L/R	8.8 vs. 6.6	43.0	.000
	Sag	f vs. p	48.0	.000
		c vs. f/p	26.5	.000
	Lat x Sag	fM to fL/R vs. pM to pL/R	20.5	.000
		cM to cL/R vs. f/pM to f/pL/R	65.7	.000

#### 9.4.6 *Response-locked ERPs: Failed Stop Trials*

Figure 9.8 depicts the average response-locked ERP waveforms for failed stop and ignore-signals trials across groups (left panel) and the difference of these waveforms (failed stop minus ignore-signal) in the Low and High groups (right panel). Ne (Low = 72.4 ms; High = 68.1 ms) showed a typical central maximum, while Pe showed a centro-parietal maximum (Low = 215.9 ms; High = 241.2 ms). As can be seen in Figure 9.8 (right panel), the difference waveforms resulted in the subtraction of activity preceding the overt response. Furthermore, horizontal eye movement was relatively minimal across groups, supporting the validity of the LRP measurement for these trials (Figure 9.8, left panel).

See Table 9.9 for means and effect summaries. Across groups, Ne amplitude showed midline, central maximas, with the midline maximum largest in the centro-parietal region. Pe amplitude showed a midline-centro-parietal maximum. Between groups, Ne and Pe amplitude showed small tendencies towards being larger in the High than Low group. There were no between-group effects for peak latency.



**Figure 9.8.** Average response-locked ERP waveforms for failed stop and no-signal trials across groups (left panel) and the difference of these trials (failed stop minus no-signal) in the High and Low groups (right panel). Notes: (1) x-axis ticks = 100 ms, (2) stimulus onset indicated by vertical bar at Pz, (3) y-axis =  $\pm 20 \mu V$ , (4) HEOG y-axis =  $\pm 15 \mu V$ .

**Table 9.9. A summary of response-locked ERP component amplitude means and statistical effects. Notes: (1) all values are in  $\mu\text{V}$ .**

Effect		Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>Amplitude</b>					
<b>Ne</b>	Lat	M vs. L/R	-11.7 vs. -9.8	20.5	.000
	Sag	c vs. f/p	-13.7 vs. -8.9	70.8	.000
	Lat x Sag	fM to fL/R vs. pM to pL/R	-9.9 to -10.2 vs. -8.6 to -7.1	7.0	.012
		cM to cL/R vs. f/pM to f/pL/R	-16.8 to -12.2 vs. -9.2 to -8.6	48.8	.000
		Low vs. High	-8.9 vs. -12.0	2.5	.124
<b>Pe</b>	Lat	M vs. L/R	15.5 vs. 12.2	52.2	.000
	Sag	c vs. f/p	14.7 vs. 12.6	17.7	.000
	Lat x Sag	fM to fL/R vs. pM to pL/R	8.7 to 8.8 vs. 18.3 to 15.4	13.7	.000
		cM to cL/R vs. f/pM to f/pL/R	19.5 to 12.4 vs. 13.5 to 12.1	67.3	.000
		Low vs. High	10.9 vs. 15.6	2.8	.103

## 9.5 Discussion

The primary aim of this study was to examine differences in stop-signal task performance and ERPs between extreme Low and High impulsivity groups, as defined by Eysenck's self-report IVE Impulsiveness subscale (1993b). Findings showed that non-clinical subjects who reported extreme low or high impulsiveness scores did not differ at the immediately overt level of performance, but showed underlying differences that reflected predominantly quantitative, rather than qualitative, differences in the response inhibition and activation processes.

### 9.5.1 Psychometric Measures of Impulsivity

In line with previous findings that Impulsiveness and Venturesomeness are related constructs (Eysenck, 1993b; Eysenck et al., 1985), the High impulsivity group also showed larger scores on the Venturesomeness subscale, relative to the Low group. Furthermore, the correlation between these two constructs was significant and similar to that found by Eysenck et al. (1985) (i.e.  $r \sim 0.4$ ), while neither subscale correlated with Empathy. Therefore, individuals who rated themselves as acting

without thinking also rated themselves as taking more deliberate risks. Interestingly, the High group also scored significantly higher than the Low group on all of the FrSBe subscales, except for Apathy, showing that impulsive subjects also reported a greater number of frontal executive dysfunctions. Correlations between Impulsiveness and FrSBe subscales supported this finding. In contrast, Venturesomeness was only related to Disinhibition. This suggests that Impulsiveness may be related to a greater degree of frontal executive dysfunctions than Venturesomeness. Finally, Disinhibition, followed by Impulsiveness, correlated positively with the most number of subscales, suggesting that these measures appear to quantify behaviours related to broad impulsivity/frontal dysfunction constructs.

#### *9.5.2 Stop-signal Task Performance*

Despite the finding that the High group rated themselves as more impulsive and having greater problems with frontal executive functions, relative to the Low group, performance findings showed no significant differences between the two groups. Although SSRT appeared to be longer in the High compared to Low group, this difference was not significant. A lack of performance differences between Low and High groups is in contrast to some studies (Logan et al., 1997; Marsh et al., 2002; Stadler & Janke, 2003), however, these previous studies used correlational techniques (Logan et al., 1997; Stadler & Janke, 2003), or a post-hoc separation of the sample pool using a median-split on impulsiveness scores (Marsh et al., 2002). In contrast, the present findings agree with studies that found no performance differences between extreme Low and High impulsivity groups (Lijffijt et al., 2004; Rodriguez-Fornells et al., 2002), and more generally, with studies showing no relationship between impulsiveness and response inhibition in the stop-signal task (Cheung et al., 2004),

go/nogo task (Horn et al., 2003; Krijns et al., 1994) or CPT (Fallgatter & Herrmann, 2001; Harmon-Jones et al., 1997). Therefore, the present findings, which showed that high degrees of the impulsiveness trait did not manifest in impulsive stop-signal task performance, are more persuasive because the low and high groups were pre-selected using extreme impulsiveness scores.

In line with the above findings, SSRT was unrelated to the Impulsiveness subscale. Furthermore, SSRT was unrelated to the FrSBe Disinhibition subscale, which measures the severity of disinhibited behaviours mediated by the orbitofrontal cortex (Stout et al., 2003). A lack of correlation with this scale suggests that stop-signal inhibition is unrelated to this region. Rather, the orbitofrontal cortex has been associated with more motivationally-driven forms of inhibition (Gray, 1987; Nigg, 2000), and with the Impulsiveness subscale (Horn et al., 2003). Therefore, the impulsiveness trait may reflect a motivational form of inhibition associated with the orbitofrontal circuit (Horn et al., 2003; Nigg, 2000). In contrast, the positive correlation between SSRT and the Executive Dysfunction subscale, which measures behaviours mediated by the dorsolateral PFC circuit (Stout et al., 2003), provides some support for the notion that stop-signal inhibition reflects an executive form of inhibition associated with this region.

### 9.5.3 *Go Response Processes*

Although the two impulsivity groups did not differ at the immediately observable level of performance, an examination of the sLRP revealed that, on stop-signals trials, response-side specific activation was greater in the High than Low group. Gray (1987) suggested that impulsivity is caused by impairment in the functioning of the behavioural activation system, which mediates ones approach to

signals of reward or non-punishment (see section 8.4). Rodriguez-Fornells et al. (2002) stated that if response initiation is a function of this system, highly impulsive individuals would be “geared to respond” (p. 663). The present findings concur with this supposition, in line with a number of previous studies showing an over-active response process in highly impulsive subjects (Jouvent & Pierson, 1998; Krijns et al., 1994; but see Brown et al., 1989 for an exception). As greater response activation in the High compared to Low group did not result in poorer inhibitory control, this suggests that response processing was counteracted by faster or greater activation of the inhibition process. An examination of stop-signal ERPs for successful trials provided further insight into the balance between response inhibition and activation in impulsive subjects.

#### *9.5.4 Stop-signal ERP Findings*

Average ERP waveforms for successful stop trials differed between groups; while the Low group showed an N1/P3 complex and a small N2 in the frontal region on the descending flank of the N1, the High group showed a very large N1/P3 complex with no evidence of an N2. The N1 showed typical midline, fronto-central maximas, while P3 had a midline-right, centro-parietal maximas. The frontal N2 did not differ across the lateral region.

Contrary to the expectation that non-clinical subjects who report high degrees of impulsiveness may suffer from response inhibition deficits (Logan et al., 1997), the High group showed evidence of enhanced stop-signal processing relative to the Low group. Firstly, N1 amplitude was larger in the High compared to Low group across the scalp, with the largest difference at the vertex. Stop N1 appears to reflect the amount of attention that is oriented towards a stop-signal (Näätänen & Picton, 1987),



and this may partly determine a subsequent successful stop (Bekker et al., 2005a). Therefore, the High group in the present study showed greater activation of this centrally-maximal, attention-related sensory process, relative to the Low group. This finding corresponds with previous studies which have found N1 augmenting with increasing stimulus intensity in High compared to Low impulsivity groups (Barratt, 1987; Barratt et al., 1987; Carrillo-de-la-Pena & Barratt, 1993), and supports the theory that impulsive individuals seek greater stimulation from their external environment (Barratt, 1983; Eysenck, 1993a; Gray, 1987; Houston & Stanford, 2005; Zuckerman, 1993).

When examination of N2 was restricted to the frontal sites, its mean amplitude did not differ between groups. In Study III (Chapter 6), a larger frontal N2 was found for successful stop trials in a slow compared to fast RT group, suggesting an association with a frontal process that reflects deliberate modulation or selection of a go or stop response (Swainson et al., 2003) during early preparational stages of processing, as opposed to an urgent inhibitory brake (reflected in the successful stop P3). Although it was expected that the Low impulsivity group may adopt a strategy that involves enforcing greater control over response execution by means of this deliberate process, manifesting in larger N2 amplitude and longer Go RT, the lack of differences between groups on these measures argues against this notion.

The key finding was faster and greater activation of the successful stop P3 in the High compared to Low group, particularly in the central region, which may reflect urgent inhibitory control near or in the motor or premotor cortex (Kok et al., 2004; Ramautar et al., 2004). It is suggested that the High group activated the inhibition process to a greater extent in order to counteract greater side-specific response activation, or alternatively, inhibited a greater number of responses in the later stages

of processing, that is, closer to the last cortical site of inhibition (Band & van Boxtel, 1999; Brunia, 1993). Greater inhibitory activation in highly impulsive individuals corresponds with the findings reported by Horn et al. (2003), who showed that scores on Eysenck's Impulsiveness (1993b) subscale correlated positively with the degree of activation in the right inferior frontal gyrus and right insula regions, during performance of a go/nogo task. Furthermore, Harmon-Jones et al. (1997) found a positive correlation between P3 amplitude and the BIS Motor Impulsiveness subscale (Barratt & Patton, 1983), although this was in an oddball task. In the CPT, previous studies have found no relationship between P3 and nogo trials (Fallgatter & Herrmann, 2001; Harmon-Jones et al., 1997), however, it has been suggested that the CPT may not be sensitive enough to evoke inhibitory processing (Fallgatter & Herrmann, 2001). Furthermore, the findings in the present study agree with those from Study IV (Chapter 7), where it was found that inducing an impulsive style of responding, by decreasing stop-signal probability, was associated with greater response activation and concurrently greater activation of the inhibition process. Therefore, in the present study, subjects who reported high degrees of the impulsiveness trait appeared to show enhanced, rather than deficient, response inhibition, suggesting a compensatory mechanism in response to enhanced response processing in these subjects.

An alternative interpretation is that a larger N1/P3 complex in the High group reflects a general cortical arousal response (Karlin & Martz, 1973), rather than increased inhibitory processing. However, the finding that N1 amplitude differed between groups for successful and failed stop trials, but that P3 amplitude only differed between groups for successful stop trials, discounts this notion. Furthermore, although studies using the oddball task have typically found reduced P3 amplitude in

High compared to Low impulsive groups, the samples in these studies were also characterised by aggression, depression, or were substance abusers (Barratt et al., 1997; Gerbing et al., 1987; Jouvent & Pierson, 1998; Mathias & Stanford, 2003).<sup>41</sup>

Slow-wave (SW) activity was examined using mean amplitude in the 400 – 700 ms latency range to obtain the MSW. Between-group differences revealed a right > left effect in the High group, while amplitude was relatively equipotential across this region in the Low group. When event-related slow-wave activity was examined after low-pass filtering (0.01 – 2 Hz) the EEG signal, a negative component (NSW) was observed in the earlier portion of the epoch, while a positive component (PSW) followed the NSW and dominated a large portion of the epoch. NSW showed a midline, fronto-central maximum and peaked earlier in the High compared to Low group, although there was no difference in amplitude. In contrast, PSW showed a midline, centro-parietal maximum and showed a tendency to be larger in the High compared to Low group. These distributions are in line with those found in previous studies using the same methodology to derive slow-wave activity (Johnstone & Barry, 1999; Johnstone et al., 2003). In general, NSW has been associated with a preparedness to respond, resulting from a lowering of neuronal thresholds (Birbaumer et al., 1990), while the PSW may reflect neuronal defacilitation and response inhibition (Birbaumer et al., 1990; Podlesny et al., 1984). Therefore, an earlier NSW in the High group may reflect faster preparation of the cognitive system for stop-signal processing, while increased PSW activity may reflect increased inhibitory

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<sup>41</sup> The type of impulsivity expressed in these samples may be more dysfunctional than that examined in the present study. This is not surprising as our subjects were screened for anxiety and severe depression using the GHQ-28. An interesting avenue of research would be to examine stop-signal task performance and ERPs in a group of subjects showing clinically significant symptoms of impulsivity, relative to the non-clinical impulsiveness trait (see Study VI, Chapter 10).

activation by this group. Therefore, underlying slow-wave activity appears to support the notion that although the High group showed an over-active response process (i.e. larger LRP activity), they compensated by preparing the system earlier with lowered neuronal thresholds for stop-signal processing (NSW), and greater inhibitory activation (PSW and successful stop P3). Furthermore, the present findings show that an examination of event-related SW activity, through an extraction of the SW delta frequency band, revealed between-group differences that were not apparent through traditional mean amplitude quantification of SW activity in the later portion of the epoch.

#### *9.5.5 Error-related Processes*

Error-related processes were examined in the stimulus- and response-locked ERP averages between Low and High impulsivity groups. Firstly, the only between-group difference for stimulus-locked ERPs on failed trials was larger N1 amplitude in the High than Low group. This effect was interpreted in line with successful stop N1. That is, enhanced N1 amplitude reflects greater attentional orienting to the stop-signal, as a means of seeking greater sensory stimulation. No other between-group differences for stimulus-locked ERP components on failed stop trials were found.

With respect to response-locked ERPs, Ne has been associated with the detection of an error (Falkenstein et al., 2000; Gehring et al., 1993), or conflict (Nieuwenhuis et al., 2003; Van Veen & Carter, 2002), while Pe may reflect a compensatory response or the affective assessment of an error (Falkenstein et al., 2000; Nieuwenhuis et al., 2001). Pailing and Segalowitz (2004) previously found that Ne amplitude differed with Neuroticism (Eysenck & Eysenck, 1969), but only in the presence of incentives. Ne amplitude did not differ between low and high groups

formed using a median-split on Neuroticism or Conscientiousness (Pailing & Segalowitz, 2004). Therefore, personality determined the manner in which incentives affected Ne amplitude, however, Ne was not directly affected by personality traits. In the present findings, Ne showed a small tendency towards greater amplitude in the High compared to Low impulsivity groups, suggesting somewhat greater error-detection in impulsive individuals. Also, a tendency towards larger Pe amplitude in the High compared to Low group suggested that impulsive subjects may have shown greater activation of compensatory or affective-related processes in response to the error (Falkenstein et al., 2000; Nieuwenhuis et al., 2001), despite no between-group differences in the frequency of failed stops. That is, the occurrence of a response on a stop-signal trial held more significance for impulsive subjects.

Finally, these findings support the notion that error-related differences in processing were best examined through response-locked, rather than stimulus-locked ERP components (see Studies III and IV, Chapters 6 and 7).

#### 9.5.6 *Summary*

In summary, the picture that has emerged across performance and ERP findings is that Low and High impulsivity groups, defined by extreme scores on Eysenck's self-report IVE Impulsiveness subscale, performed similarly in the stop-signal task, but showed underlying differences in response activation and inhibition processes. Specifically, the High group displayed larger LRP amplitude, reflecting greater side-specific response activation. However, a larger successful stop P3 showed that subjects were able to compensate for enhanced response processing by activating the inhibition process to a greater extent, or alternatively, by stopping responses more frequently at the last cortical site of inhibition (i.e. the primary motor

cortex). A tendency towards larger PSW activity in the High compared to Low group supported the interpretation of enhanced inhibitory processing. Furthermore, an enhanced N1 for successful and failed stop trials in the High compared to Low group supported the notion that impulsivity predisposes individuals to seek greater sensory stimulation. Finally, the groups showed a tendency towards differing in processes related to the detection (Ne) and affective or compensatory processing of failed stop errors (Pe). Together these findings showed that subjects who reported high degrees of the impulsiveness trait did not display impulsive stop-signal task performance overtly. Rather, these subjects adopted a compensatory mechanism of increased inhibitory activation to counteract an impulsive response style. Finally, findings suggest that impulsive behaviours, as measured by Eysenck's Impulsiveness trait (1993b), were not mediated by response inhibition deficits, but rather, over-active response processing.

#### *9.5.7 Implications*

Although subjects in the present study reported a greater frequency of impulsive traits and frontal executive dysfunctions, they were able to compensate accordingly and perform a response inhibition task at a comparable level to unimpulsive subjects. This suggests that poor inhibitory control in the stop-signal task is not related to impulsive behaviours generally, but rather, may be restricted to a particular type of impulsivity. It was suggested earlier that stop-signal inhibition reflects an executive (not motivational) form of inhibition that may be mediated by the dorsolateral PFC circuit; therefore, deficits in this circuit may be associated with a more dysfunctional form of impulsivity. The following study examined stop-signal task performance and associated ERPs in a group of adults with ADHD, who are

characterised by impulsive-type behaviours (among other symptoms). The questions put forward by this study are: (1) what is the nature of the inhibitory problem in adults with ADHD, and (2) does a common mechanism underlie the impulsiveness trait and impulsivity symptoms in ADHD (i.e. over-active response processing)?

## **10. Study VI - ADHD and the impulsiveness trait in simple and selective stop-signal tasks**

### **10.1 Abstract**

Deficient response inhibition has been implicated in underlying symptoms of impulsivity in children with ADHD, however, few studies have examined this deficit in adults with the disorder. In the present study, a group of adults diagnosed with ADHD ( $n = 10$ ) performed simple and selective versions of the stop-signal task, and were compared to the non-clinical Low ( $n = 10$ ) and High ( $n = 10$ ) impulsivity groups from Study V (Chapter 9). Findings showed a slower inhibitory response and flatter inhibition function, but comparable average inhibition probability, in the ADHD group, relative to the two non-clinical groups. Response-related processes appeared to be relatively intact in the ADHD group, who showed no difference in LRP amplitude relative to the Low group, but were reduced relative to the High group. Stop-signal processing, however, was impaired in the ADHD group, with a reduced central N1 and globally reduced P3, relative to the non-clinical groups, suggesting a deficit in switching attention to the stop-signal and reduced activation of the stop-signal inhibition process. The comparison of simple and selective conditions suggested that adults with ADHD, analogous to healthy controls, did not use a differential inhibition process during selective stopping, although underlying slow-wave activity showed an atypical pattern between conditions. The findings suggest that adults with ADHD are characterised by a distinct pattern of stop-signal processing deficits that results in a more dysfunctional form of overt impulsivity than that observed for the impulsiveness trait.



## 10.2 Introduction

Although evidence suggests that adults exhibit fewer symptoms of ADHD with time, it appears that the impairment caused by the remaining symptoms becomes more pronounced (Barkley, 2000). A review of studies (see section 8.7.1) shows that there is a tendency towards a longer SSRT in adults with ADHD, relative to controls (Aron et al., 2003a; Bekker et al., in press; Bekker et al., submitted; see Epstein et al., 2001 for an exception; Murphy, 2002; Ossmann & Mulligan, 2003), and that this deficit may be more pronounced in adults than in children with the disorder (Lijffijt et al., 2005). ERPs further support impaired stop-signal processing in adults with ADHD, both at early sensory and later inhibitory stages of processing. In the simple stop-signal task, the reduced difference in N1 amplitude between successful and failed trials in an ADHD compared to control group has been interpreted as reflecting an impairment in switching attention to the stop-signal, which may partly contribute to subsequent poorer inhibitory activation (Bekker et al., submitted). Furthermore, delayed P3 peak latency has been found to be associated with slower SSRT in adults with ADHD (Bekker et al., submitted), while another study found reduced amplitude of the fronto-central nogo P3 in adults with a history of childhood ADHD (Fallgatter et al., 2005). Therefore, response inhibition in adults with ADHD may be slower and under-active.

As outlined previously, impulsivity may be due to deficient response inhibition or over-active response processing (Gray, 1987; Logan, 1994). In the preceding study (Study V, Chapter 9), it was found that the mechanism underlying impulsive behaviours in a non-clinical “impulsive” group may be due to an over-active response process (Eysenck, 1993a; Gray, 1987), rather than deficient response inhibition (Logan et al., 1997). Adults with ADHD similarly display high degrees of

impulsive behaviours, however there is a general lack of studies examining the processes underlying this impulsivity. If impulsivity lies on a continuum with ADHD, representing the extreme end of the impulsiveness personality trait (Price, Simonoff, Waldman, Asherson, & Plomin, 2001; Sonuga-Barke, 1998), one may expect to find that this is (at least partly) due to over-active response processing (Study V, Chapter 9), manifesting in larger LRP amplitude. Furthermore, ADHD subjects should show larger scores on Eysenck's Impulsiveness subscale (1993b), indicating a greater severity in impulsivity, relative to the High impulsivity group.

A more complicated form of inhibitory processing, where stimulus discrimination is included in the stop-signal inhibitory response, was previously examined in non-clinical adults in Study II (Chapter 5). It was anticipated that the additional processes (i.e. stimulus discrimination and response selection) and increased cognitive workload (i.e. retaining the stimulus-response relationship in working memory) would be associated with prolonged stop-signal processing and the activation of a different inhibition process. However, simple and selective conditions showed a similar SSRT and topographic distribution of the successful stop P3, which suggested that healthy adults evoked inhibitory processing in a similar, fast and non-selective manner across conditions. In children with ADHD, Bedard et al. (2003) found a longer SSRT and more variable go response, but no difference in go response speed, relative to a control group, in a selective stop-signal task. Therefore, children with ADHD have shown impairments in selective inhibitory processing, as well as in simple stop-signal tasks (see Oosterlaan et al., 1998 for a review). However, selective inhibition in this study was not compared to simple inhibition, therefore, it is not known whether selective inhibition impairments are more pronounced in ADHD than those associated with simple inhibition. Furthermore, there have been, no studies to-

date that have examined selective inhibition in adults with ADHD. One of the aims of the present study was to examine whether stop-signal inhibition is deficient in adults with ADHD, and whether this deficit (if one exists) is greater in a selective stop-signal task.

In summary, the aims of the present study were to examine whether, like children with ADHD, adults with the disorder may suffer from deficient response inhibition in simple and selective stop-signal tasks, relative to non-clinical groups, but in particular, relative to a Low impulsivity group. Poorer inhibitory performance in the ADHD group was expected to manifest in a slower SSRT, reduced inhibition probability and a flatter inhibition function. In line with previous findings, it was hypothesised that stop-signal processing deficits may be partly due to poor attentional orienting to the stop-signal (reduced N1 amplitude), and a deficient and/or delayed inhibition process (successful stop P3). Furthermore, it was found in the previous study (Chapter 9) that impulsivity in adults who reported high degrees of Eysenck's impulsiveness trait (1993b) may be mediated by over-active response processing. Therefore, we examined whether adults with ADHD may show even greater response preparation (i.e. larger LRP amplitude) and larger Impulsiveness scores, relative to the High impulsivity group, indicating a greater severity in impulsivity. SW components were also examined to determine differences in general neuronal excitation and inhibition. Finally, error-related processes were examined in response-locked ERP components to determine whether adults with ADHD may show deficiencies in error detection and compensatory processes.

### 10.3 Method

#### 10.3.1 Subjects

Thirty adults aged 19 years 0 months to 44 years 8 months participated in this study and formed three groups: Low-Impulsive (Low), High-Impulsive (High) and ADHD. The Low (mean age = 23.3, SD = 3.0 years) and High groups (mean age = 21.3, SD = 3.4 years) were formed by matching subjects from Study V (Chapter 9) with adults in the ADHD group, as close as possible by age (mean age = 26.3, SD = 7.2 years), resulting in 10 subjects per group. Subjects in the ADHD group had received a diagnosis of ADHD by a clinical practitioner in adulthood according to the DSM-IV (American Psychiatric Association, 1994) (3 subjects had also received a childhood diagnosis of ADHD). Furthermore, all subjects satisfied criteria in the ADHD Self-Report Scale for adults (ASRS) (Adler & Cohen, 2003; see section 8.6.2). Five subjects in the ADHD group were taking stimulant medication (either Ritalin or Dexamphetamine) as treatment for the disorder at the time of testing, although all subjects were free of all medications, as well as other stimulants, for a minimum of 24 hours prior to the test session. This period is sufficient to remove the residual effects of the medication as each has a half-life of approximately 10 hours (Hunt, Mandl, Lau, & Hughes, 1991).

Adults with ADHD were recruited through advertisements that were distributed to local ADHD support groups. Those who were interested contacted the researcher by phone or email. Thereafter, the researcher conducted a phone interview using a semi-standardised format to screen individuals for a valid diagnosis of ADHD and the identification of any other health concerns that may adversely affect performance in the study. Subjects were also asked to answer questions from the Adult ADHD Self-Report Scale version 1.1 (ASRS-v1.1; Adler & Cohen, 2003;

World Health Organisation [WHO], 2003), a scale that measures the frequency of ADHD symptoms (based on the DSM-IV-TR criteria) (American Psychiatric Association, 2000)) using a 5-point Likert scale (Never to Very Often). Subjects who fulfilled the criteria were asked if they would like to book an appointment for the experimental session, after which, an information pack was sent out detailing the experimental procedures, aims, maps of the testing location, and details of meeting points.

After the experimental session, subjects were included if they had obtained a standardised score of 80 or greater on the RPM (Raven, 2000), and if they had never suffered an epileptic seizure, serious head injury, period of unconsciousness or any other psychiatric condition. The GHQ-28 (see section 9.3.4.1 for details) was used to screen for anxiety and severe depression (Goldberg & Hillier, 1979). Each subject had normal or corrected-to-normal vision and was a native English speaker. The number of left-handed subjects in the Low, High and ADHD groups were 1, 2 and 1, respectively. Informed consent was obtained from all subjects after the testing equipment had been explained, with the option to withdraw without penalty.

### **10.3.2 Procedure**

All procedural details and specifications for the stop-signal task are as outlined in Study II (Chapter 5). That is, all subjects completed the simple and selective conditions of the stop-signal task, and findings from both conditions are presented here. Only statistical effects that interacted with Group are reported.<sup>42</sup> See Study II

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<sup>42</sup> An examination of simple vs. selective stopping in Low and High impulsivity groups did not reveal any meaningful significant effects (Study V, Chapter 9).

(Chapter 5) for a comparative investigation of simple and selective inhibition in a group of non-clinical adults.

Repeated-measures ANOVAs were used for the analysis of psychometric measures ( $df = 2,27$ ) with “Group” (ADHD, Low, High) as a between-subjects factor. Bonferroni post-hoc tests were used to examine between-subjects differences. MANOVAs were used for the analysis of performance and ERP measures ( $df = 1,27$ ) with the within-subjects factor “Condition” comparing simple and selective conditions, and the between-subjects factor “Group”. Within Group, simple contrasts compared the ADHD with the Low and High groups, respectively. It should be noted that because the ADHD group differed significantly from the Low and High groups in age, this was covaried for in the original analyses. However, as age did not interact with any ERP amplitude or performance measure significantly, analyses were re-run without the age factor removed.

## **10.4 Results**

### *10.4.1 Psychometric Measures*

Table 10.1 provides the summary statistics for the psychometric measures in the ADHD, Low and High groups. Within the IVE, a main effect was found only for the Impulsiveness subscale. Post-hoc tests revealed larger scores in the ADHD group compared to the Low group ( $p < .001$ ), but not the High group ( $p = .169$ ). Within the FrSBe, main effects were found for the Disinhibition, and Executive Dysfunction subscales, as well as the Overall Frontal Systems scale, but not the Apathy subscale. These effects were due to larger scores in the ADHD group compared to the Low

group for the three subscales ( $p < .01$ ), although there was no differences between ADHD and High groups ( $p > .1$ ).

**Table 10.1. Summary statistics for the psychometric measures in the Low, High and ADHD groups. Note: (1) statistics refer to Group main effects, (2) Degrees of Freedom = 2, 27.**

Psychometric	Low	High	ADHD	<i>F</i>	<i>P</i>
<b>IVE</b>					
Impulsiveness	2.1 (1.0)	15.2 (1.4)	13.5 (3.4)	103.0	.000
Venturesomeness	7.4 (2.6)	11.0 (4.2)	9.7 (4.0)	2.5	.102
Empathy	14.7 (3.3)	14.5 (2.7)	13.3 (3.1)	0.6	.552
<b>FrSB</b>					
Apathy	58.8 (14.9)	63.4 (8.7)	70.9 (17.9)	1.8	.184
Disinhibition	49.8 (10.9)	74.0 (18.7)	80.8 (18.4)	9.9	.001
Executive Dysfunction	52.4 (8.3)	70.7 (9.2)	77.0 (13.9)	14.3	.000
Overall Frontal Systems	54.1 (10.1)	74.2 (12.1)	79.4 (15.0)	11.3	.000

#### 10.4.2 Performance Measures

Statistically significant effects involving Condition were reported if they interacted with Group ( $df = 1, 27$  unless otherwise stated). Table 10.2 provides the means and standard deviations for the performance measures.

The ADHD group showed a greater likelihood of committing an omission error relative to the High group ( $F = 4.9, p < .05$ ), while the difference between ADHD and Low groups (ADHD > Low) approached significance ( $F = 3.2, p = .085$ ). Go MRT and the proportion of choice errors did not differ between groups. Mean RT for failed stop trials (FSRT) did not differ between groups, but was shorter than Go MRT across groups and conditions ( $F = 120.7, p < .001$ ). SSRT differed between groups, with the ADHD group showing a larger SSRT relative to the Low ( $F = 5.5, p < .05$ ) and High groups ( $F = 5.3, p < .05$ ). Group did not interact with Condition for any of the above measures.

**Table 10.2. Means and standard deviations (in brackets) of performance measures for the simple and selective conditions in the Low, High and ADHD groups.**

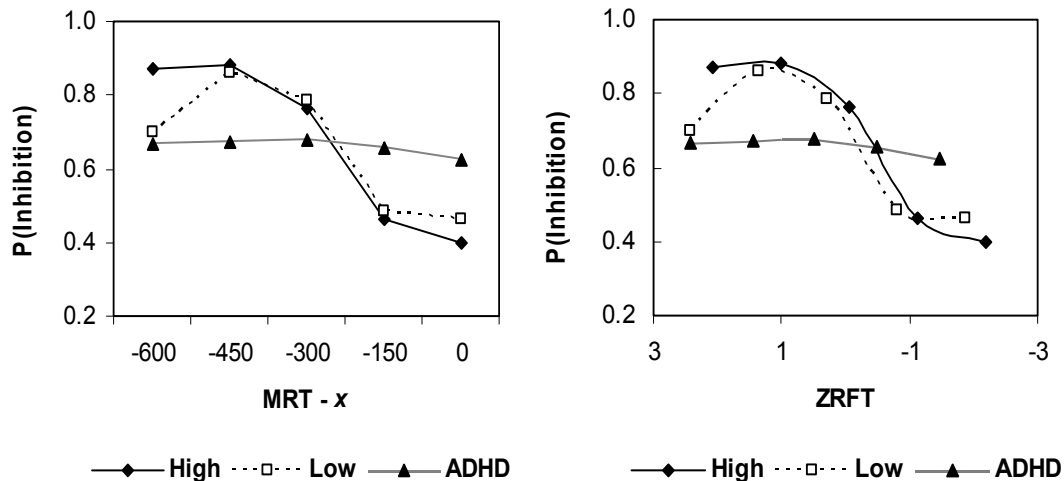
	Simple Condition			Selective Condition		
	Low	High	ADHD	Low	High	ADHD
<b>Go MRT</b>	605.4 (160.3)	542.1 (131.5)	662.7 (198.8)	676.0 (217.9)	592.2 (223.9)	652.5 (159.1)
<b>Omissions</b>	0.85 (0.89)	0.43 (0.45)	2.1 (2.2)	0.97 (1.8)	0.54 (0.7)	2.8 (0.4)
<b>Choice</b>	6.8 (1.3)	8.2 (3.1)	8.9 (2.8)	11.3 (3.2)	12.3 (5.1)	13.7 (4.8)
<b>SSRT</b>	246.1 (112.4)	269.7 (79.2)	304.6 (55.5)	252.2 (118.8)	230.8 (83.6)	346.2 (64.7)
<b>FSRT</b>	196.4 (58.8)	165.5 (57.3)	213.5 (82.0)	221.3 (81.8)	219.7 (64.5)	249.9 (94.1)

Notes: (1) Go MRT = Primary task mean reaction time to Go stimuli on no-signal trials; FSRT = Mean reaction time to Go stimuli for failed stop trials; SSRT = Mean stop-signal reaction time; Choice = choice errors (i.e. press lion when apple and vice versa), (2) RTs in ms, (3) errors as percentages.

Figure 10.1 shows inhibition probability as a function of stop-signal delay (left panel) and ZRFT (right panel), across condition. Across groups, inhibition probability decreased linearly with an increase in stop-signal delay ( $F = 39.2$ ,  $p < .001$ ). Although average inhibition probability did not differ between groups ( $F < 1$ ), the linear effect of the inhibition function was greater in the Low ( $F = 25.7$ ,  $p < .001$ ) and High groups ( $F = 25.3$ ,  $p < .001$ ) relative to the ADHD group. As can be seen in Figure 10.1 (right panel), plotting inhibition probability as a function of ZRFT appeared to fail to align the inhibition function in the ADHD group with that of the non-clinical groups. Between conditions, the Low group showed a greater linear effect in the simple compared to selective condition, while this effect did not differ between conditions in the ADHD group ( $F = 6.8$ ,  $p < .05$ ).

Correlations were performed between the psychometric and performance measures in the ADHD group only. A significant relationship was found between selective SSRT and the FrSBe Executive Dysfunction subscale ( $r = .64$ ,  $p < .05$ ).





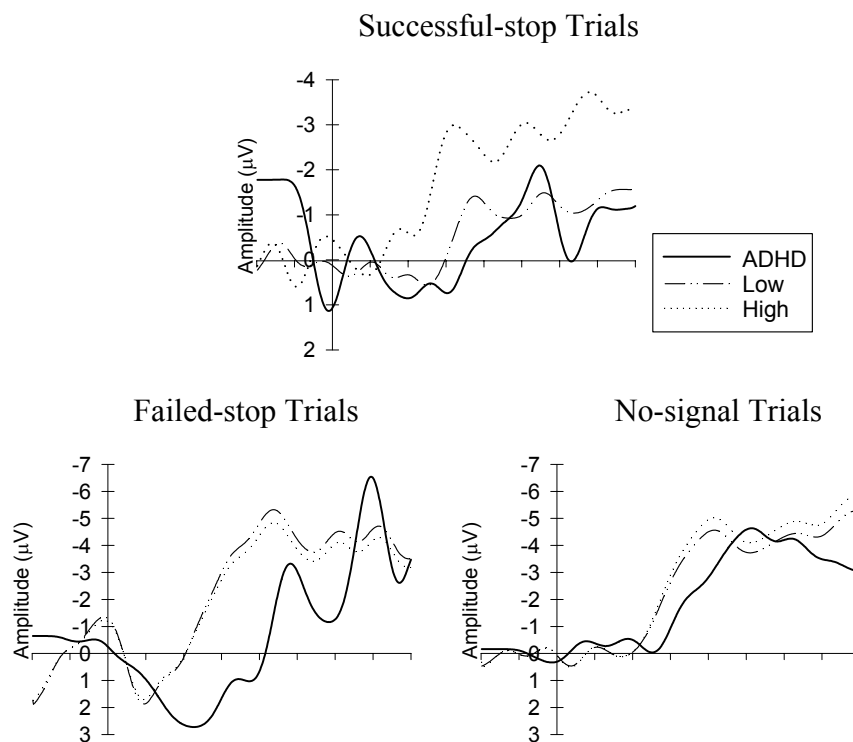
**Figure 10.1. Inhibition probability as a function of stop-signal delay (MRT – x) (left panel) and ZRFT (right panel). Note: (1) the number of subjects that did not receive a stop-signal at the (MRT – 600) ms delay in the Low, High and ADHD groups were: 2, 4 and 3 in the simple condition, and 1, 3 and 1 in the selective condition, respectively (2 subjects across both conditions), and (2) statistical effects exclude this delay.**

#### 10.4.3 Lateralised Readiness Potential (LRP)

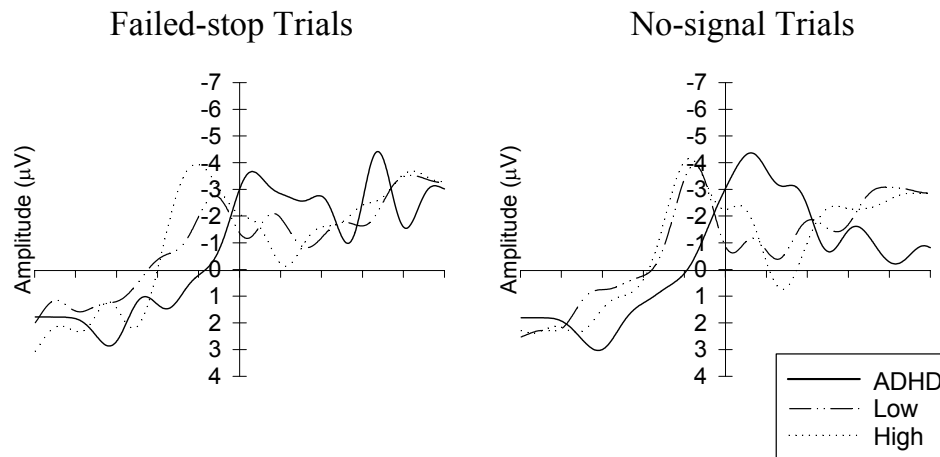
Many subjects in the selective condition displayed noisy LRP waveforms, resulting in an unequal number of subjects between groups; therefore, statistical analyses were restricted to the simple condition only.

Figure 10.2 depicts the average LRP waveforms in each group for successful stop, failed stop and no-signal trials. Across Group, LRP amplitude was larger for failed stop compared to no-signal trials ( $F = 10.3, p < .01$ ), and the mean of these trials was larger compared to successful stop trials ( $F = 26.2, p < .001$ ). Across Trial, LRP amplitude was reduced in the ADHD compared to the High ( $F = 6.8, p < .05$ ), but not Low, group ( $F = 1.3, p = .265$ ). Furthermore, the onset of the stimulus-locked LRP showed a tendency towards being delayed in the ADHD compared to High ( $F = 3.3, p = .08$ ) but not Low group ( $F < 1$ ). These latter effects did not differ between trials.

With respect to the response-locked LRP, its amplitude was larger for failed stop compared to no-signal trials ( $-7.9$  vs.  $-6.3$   $\mu\text{V}$ ,  $F = 4.3$ ,  $p < .05$ ), while the onset-to-RT interval was longer for no-signal trials (mean difference =  $49.6$  ms,  $F = 6.5$ ,  $p < .050$ ). Furthermore, across Trial, the onset-to-RT interval was reduced in the ADHD compared to Low (mean difference =  $119.8$  ms,  $F = 4.8$ ,  $p < .05$ ) and High groups (mean difference =  $201.6$  ms,  $F = 13.6$ ,  $p < .01$ ; see Figure 10.3).



**Figure 10.2.** Stimulus-locked LRP waveforms for successful stop, failed stop and no-signal trials in the Low, High and ADHD groups. Notes: for this and subsequent LRP figures, (1) x-axis marks every 100 ms, (2) vertical bar indicates go stimulus onset, (3) negative-going amplitude is up.



**Figure 10.3. Response-locked LRP waveforms for failed stop and no-signal trials in the Low, High and ADHD groups.**

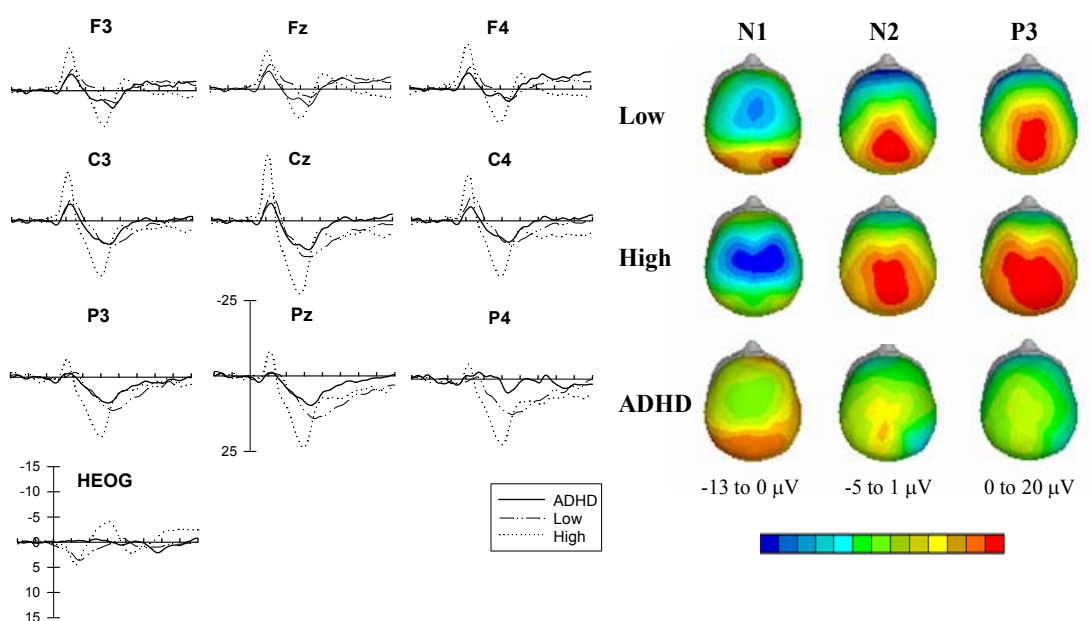
#### *10.4.4 Stimulus-locked ERP Components: Successful Stop Trials*

Figure 10.4 depicts the stimulus-locked average ERP waveforms and topographic maps for successful stop trials in the simple (upper panel) and selective (lower panel) conditions. For means and effect summaries, see Table 10.3 for the ADHD versus Low group comparison and Table 10.4 for the ADHD versus High group comparison. Effects in the following section are divided into: (a) across conditions, and (b) between simple and selective conditions.

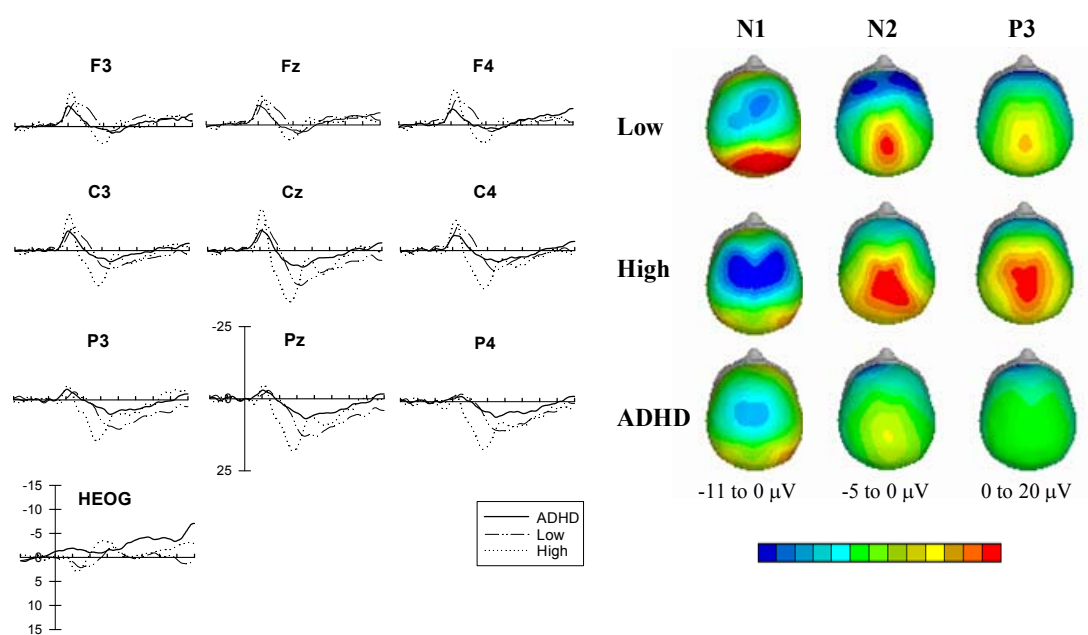
##### **10.4.4.1 Across Conditions**

**N1:** N1 amplitude was larger in the High compared to ADHD group across the scalp, and this difference was largest in the central region (see Figure 10.5, upper left panel). Although there was no main effect between Low and ADHD groups, the central maximum was reduced in the ADHD group relative to the former group. Furthermore, a fronto-centrally maximal lateral > midline effect occurred in the High group, with this effect reduced in the ADHD group.

### Simple Condition



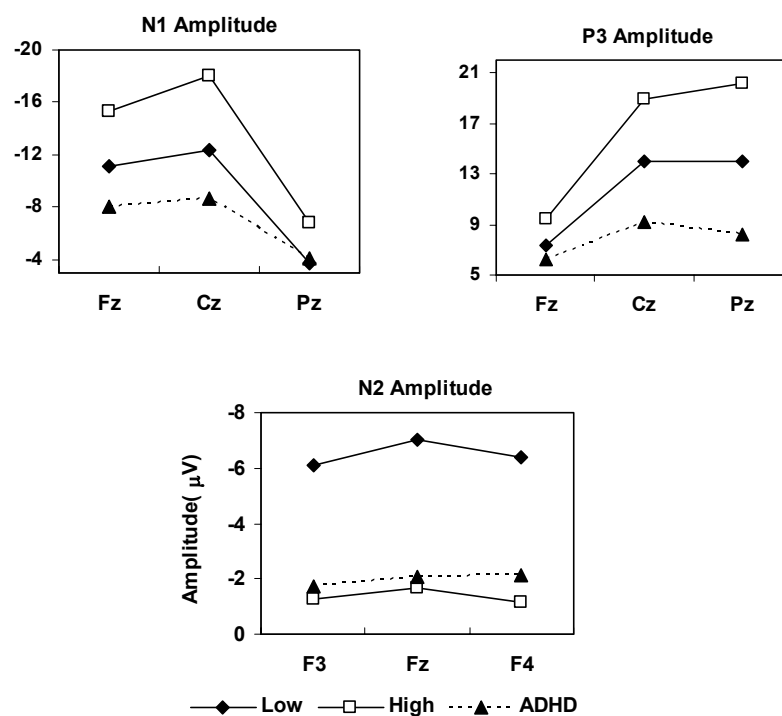
### Selective Condition



**Figure 10.4.** Stimulus-locked average ERP waveforms and topographic head maps for successful stop trials in the simple (upper panel; y-axis =  $\pm 25 \mu V$ ) and selective conditions (lower panel; y-axis =  $\pm 25 \mu V$ ). Notes: (1) x-axis ticks = 100 ms, (2) y-axis vertical bar indicates stop-signal onset, (3) negative-going amplitude is up.

**N2:** Although there were no significant effects for N2 mean amplitude when analyses were restricted to the frontal sites, there was a tendency towards a Group main effect with larger amplitude in the Low compared to ADHD group (see Figure 10.5, bottom panel). However, this difference did not differ across the lateral sites.

**P3:** The ADHD group showed a reduced P3 amplitude across the scalp relative to the High group, and this difference was largest in the centro-parietal region, while there was a tendency towards a reduction relative to the Low group ( $p = .092$ ) (see Figure 10.5, upper right panel).



**Figure 10.5.** Amplitude at the midlines sites for N1 and P3, and across the frontal lateral sites for N2 in the Low, High and ADHD groups. Notes: (1) All components shown with larger amplitudes at the top of y-axis depending on the polarity of the component.

#### 10.4.4.2 Simple vs. Selective Inhibition

**N1:** Although the Low and High groups showed a central maximum for N1 amplitude that was larger in the simple than selective condition, the ADHD group showed a reduced central maximum that did not differ between conditions. Across the laterality factor, a midline > lateral effect was found to be larger in the simple than selective condition in the ADHD group, with this effect reduced in the High group. Furthermore, a centrally-maximal midline > lateral effect was reduced in the simple compared to selective condition in the ADHD group, but was larger in the simple than selective condition in the High group, while the Low group showed no difference in this effect between conditions. With respect to latency, N1 peaked later in the selective than simple condition in the ADHD group; the High group showed the opposite effect.

There were no between-group differences involving Condition for N2 or P3 amplitudes or latencies.

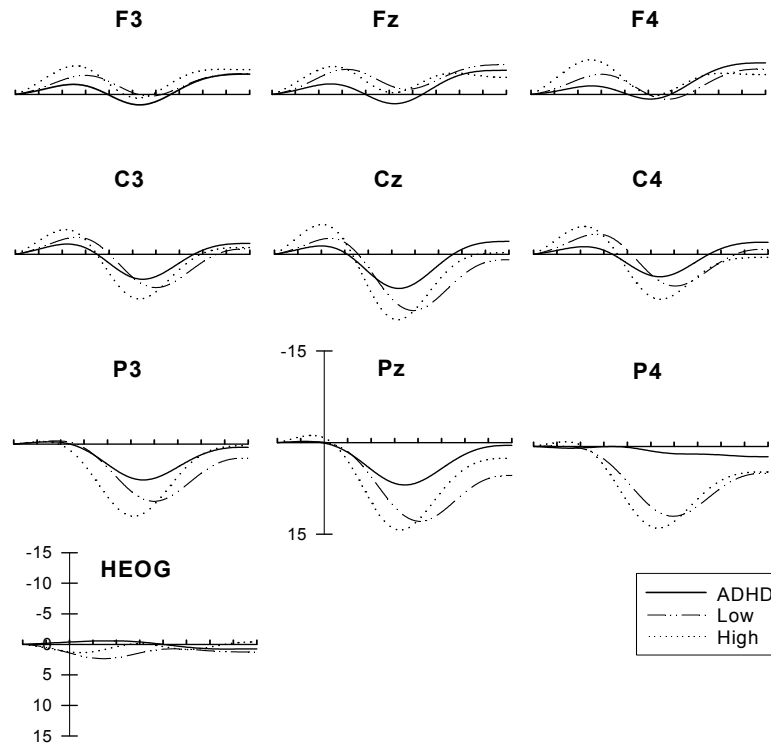
**Table 10.3. A summary of ERP component amplitude analyses and means for successful stop trials between Low and ADHD groups. Notes: (1) all values are in  $\mu\text{V}$ .**

	Effect	Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>Low vs. ADHD: Amplitude</b>					
N1	G x S	c vs. f/p	ADHD: -8.7 vs. -6.6 Low: -12.4 vs. -7.4	5.7	.025
	G x C x S	c vs. f/p	ADHD sim: -7.6 vs. -5.2; sel: -9.8 vs. -6.9 Low sim: -13.3 vs. -7.6; sel: -11.6 vs. -7.2	5.6	.025
	G x C x L x S	cM to cL/R vs. f/pM to f/pL/R	ADHD sim: -7.4 to -7.1 vs. -5.2 to -5.2 ADHD sel: -11.1 to -9.2 vs. -7.8 to -6.5 Low sim: -14.6 to -12.6 vs. -8.2 to -7.3 Low sel: -12.9 to -10.9 vs. -7.7 to -7.0	6.3	.019
N2	G	ADHD vs. Low	1.1 vs. -3.1	2.5	.129
P3	G	ADHD vs. Low	7.9 vs. 11.7	3.0	.092

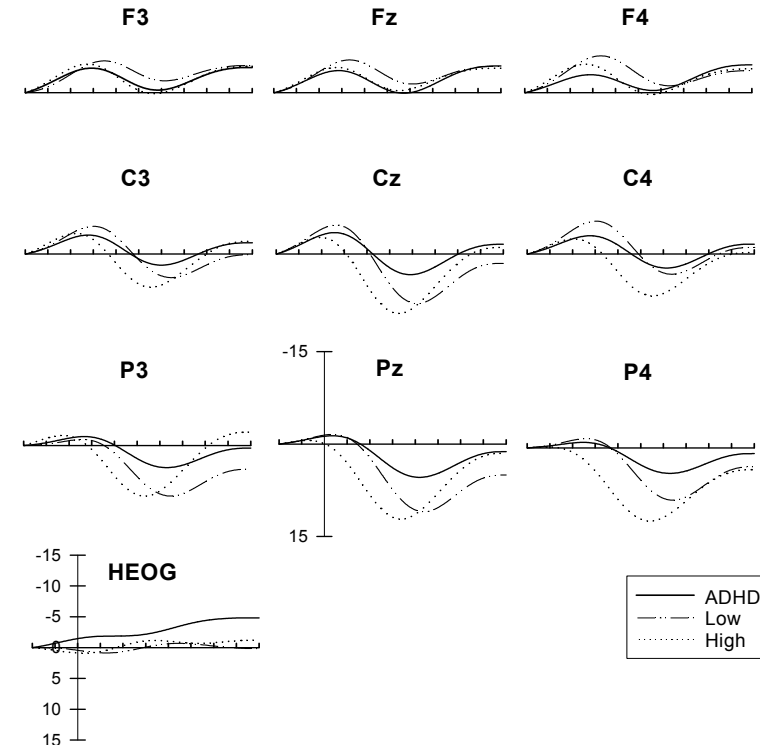
**Table 10.4. A summary of ERP component amplitude analyses and means for successful stop trials between High and ADHD groups. Notes: (1) all values are in  $\mu\text{V}$ .**

Effect		Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>High vs. ADHD: Amplitude</b>					
N1	G	ADHD vs. High	-5.9 vs. -13.4	10.2	.004
	G x C	Simple vs. Selective	ADHD: -6.0 vs. -7.9 High: -15.8 vs. -10.9	15.8	.000
	G x S	c vs. f/p	ADHD: -8.7 vs. -6.6	18.2	.000
		c vs. f/p	High: -18.0 vs. -11.0		
	G x C x L	M vs. L/R	ADHD sim: -17.6 vs. -15.0 ADHD sel: -11.1 vs. -10.8 High sim: -6.3 vs. -5.9 High sel: -8.9 vs. -7.4	35.2	.000
	G x C x S	c vs. f/p	ADHD sim: -7.6 vs. -5.2; sel: -9.8 vs. -6.9 High sim: -21.8 vs. -12.9; sel: -14.3 vs. -4.5	29.8	.000
	G x L x S	fM to fL/R vs. pM to pL/R	ADHD: -8.7 to -7.7 vs. -4.3 to -4.0 High: -13.7 to -16.0 vs. -7.8 to -6.3	5.6	.026
		cM to cL/R vs. f/pM to f/pL/R	ADHD: -9.7 to -8.2 vs. -6.5 to -5.8 High: -21.6 to -16.3 vs. -10.8 to -11.2	16.3	.000
	G x C x L x S	cL to cR vs. f/pL to f/pR	ADHD sim: -7.4 to -7.1 vs. -5.2 to -5.2 ADHD sel: -11.1 to -9.2 vs. -7.8 to -6.5 High sim: -26.8 to -19.3 vs. -13.1 to -12.8 High sel: -16.4 to -13.2 vs. -8.5 to -9.6	5.1	.032
N2	No effects				
P3	G	ADHD vs. High	7.9 vs. 16.2	13.9	.001
	G x S	f vs. p	ADHD: 6.2 vs. 8.2 High: 9.4 vs. 20.1	10.5	.003
		c vs. f/p	ADHD: 9.2 vs. 7.2 High: 18.9 vs. 14.8	4.6	.042
	G x L x S	cM to cL/R vs. f/pM to f/pL/R	ADHD: 11.5 to 8.0 vs. 8.5 to 6.5 High: 23.4 to 16.7 vs. 15.6 to 14.3	8.1	.008
<b>Latency</b>					
N1	G x C	Simple vs. Selective	ADHD: 141.0 vs. 125.8 ms High: 119.1 vs. 123.8 ms	34.3	.049
P3	G	ADHD vs. High	327.4 vs. 289.5 ms	3.7	.064

### Simple Condition



### Selective Condition



**Figure 10.6.** Stimulus-locked, event-related, slow-wave average ERP waveforms (i.e. 0.01 to 2 Hz) for successful stop trials in the simple (left panel; y-axis =  $\pm 15 \mu\text{V}$ ) and selective conditions (right panel; y-axis =  $\pm 15 \mu\text{V}$ ). Notes: (1) x-axis ticks = 100 ms, (2) y-axis vertical bar indicates stop-signal onset, (3) negative-going amplitude is up.



#### *10.4.5 Slow-wave (0.01 to 2Hz): Successful Stop Trials*

Figure 10.6 depicts the stimulus-locked event-related slow-wave ERP waveforms for successful stop trials in the simple (left panel) and selective (right panel) conditions. See Table 10.5 for means and effect summaries.

##### **10.4.5.1 Across Conditions**

In the ADHD group, NSW amplitude was reduced relative to the Low and High groups across the entire scalp, although this difference was largest in the fronto-central region for the Low group and in the central region for the High group. Furthermore, a fronto-central midline > lateral effect was larger in the High compared to ADHD group.

PSW amplitude was also reduced in the ADHD group compared to the Low and High groups across the entire scalp, although these differences were not localised to any particular region.

##### **10.4.5.2 Simple versus Selective Inhibition**

While the Low and High groups showed larger NSW and PSW amplitude in the selective compared to simple condition, the ADHD group showed the opposite effects. Furthermore, the High group showed a parietal > frontal effect for PSW that was larger in the simple than selective condition, with this effect reduced in the ADHD group.

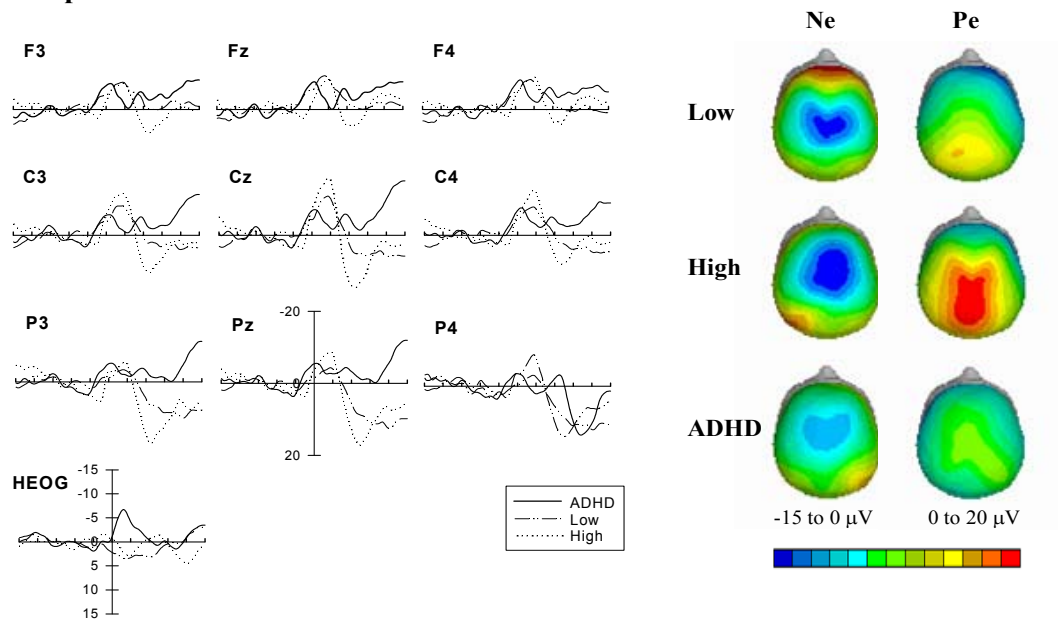
**Table 10.5. A summary of ERP component amplitude analyses and means results for successful stop trials. Notes: (1) all values are in  $\mu\text{V}$ .**

Effect	Contrast	Effect Details	<i>F</i>	<i>p</i>
<b><u>Low vs. ADHD: Amplitude</u></b>				
<b>NSW</b> G	ADHD vs. Low	-2.8 vs. -7.0	13.8	.001
	G x C	Simple vs. Selective	13.8	.001
		ADHD: -1.9 vs. -3.8		
		Low: -3.1 vs. -10.9		
G x S	f vs. p	ADHD: -3.1 vs. -1.9	4.9	.036
		Low: -8.7 vs. -3.2		
	c vs. f/p	ADHD: -3.1 vs. -2.5	17.1	.000
		Low: -9.2 vs. -6.0		
<b>PSW</b> G	ADHD vs. Low	3.8 vs. 8.4	8.1	.008
	G x C	Simple vs. Selective	8.5	.007
		Low: 5.9 vs. 10.8		
<b><u>High vs. ADHD: Amplitude</u></b>				
<b>NSW</b> G	ADHD vs. High	-2.8 vs. -7.5	17.5	.000
	G x C	Simple vs. Selective	12.5	.001
		ADHD: -1.9 vs. -3.8		
		High: -3.7 vs. -11.3		
G x S	c vs. f/p	ADHD: -3.1 vs. -2.5	30.4	.000
		High: -10.3 vs. -6.2		
G x L x S	fM to fL/R vs. pM to pL/R	ADHD: -3.3 to -2.5 vs. -2.2 to -2.6	4.5	.042
		High: -9.8 to -5.9 vs. -8.8 to -6.1		
	cM to cL/R vs. f/pM to f/pL/R	ADHD: -3.9 to -2.4 vs. -2.8 to -2.6	10.5	.003
		High: -12.1 to -6.7 vs. -9.3 to -6.0		
<b>PSW</b> G	ADHD vs. High	3.8 vs. 9.4	12.3	.002
	G x C	Simple vs. Selective	5.2	.031
		ADHD: 4.4 vs. 3.1		
		High: 7.7 vs. 11.2		
G x C x S	f vs. p	ADHD sim: 2.0 vs. 5.6; sel: 0.5 vs. 5.3	4.3	.049
		High sim: 1.0 vs. 13.2; sel: 5.9 vs. 14.4		
G x L x S	cM to cL/R vs. f/pM to f/pL/R	ADHD: 15.3 to 10.9 vs. 13.1 to 7.8	7.1	.013
		High: 13.9 to 9.5 vs. 9.6 to 5.9		

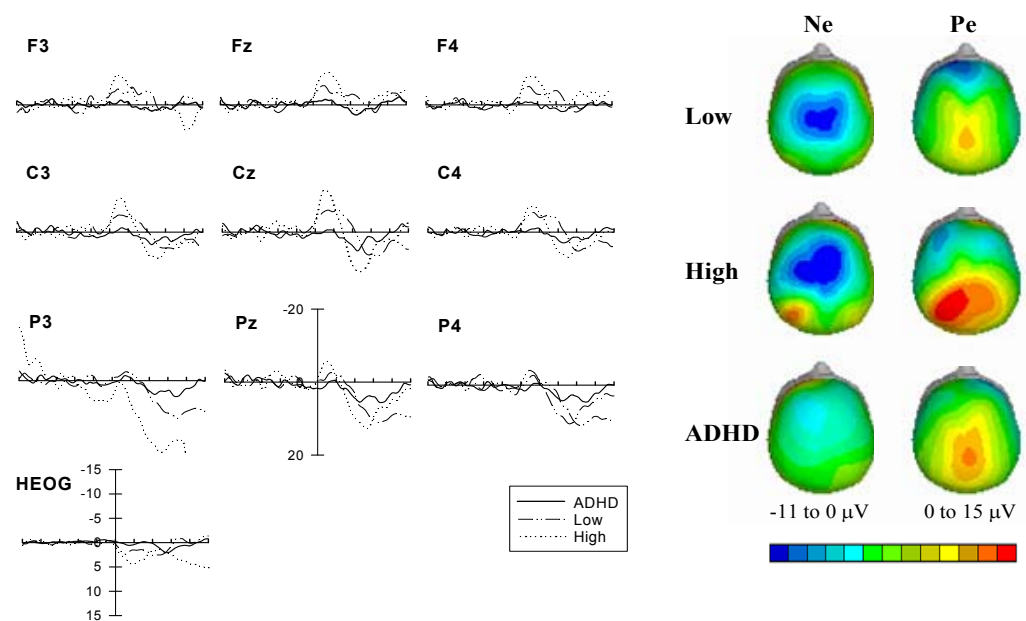
#### 10.4.6 Response-locked ERP Components: Failed Stop Trials

Figure 10.7 depicts the response-locked average ERP difference waveforms (i.e. failed stop minus ignore-signal trials) and topographic head maps in the simple (upper panel) and selective (lower panel) conditions. See Table 10.6 for means and effect summaries.

### Simple Condition



### Selective Condition



**Figure 10.7.** Response-locked average ERP difference waveforms and topographic head maps for failed stop trials in the simple (upper panel; y-axis =  $\pm 20 \mu\text{V}$ ) and selective conditions (lower panel; y-axis =  $\pm 20 \mu\text{V}$ ). Notes: (1) x-axis ticks = 100 ms, (2) y-axis bar indicates response onset, (3) negative-going amplitude is up.

#### **10.4.6.1 Across Conditions**

Ne amplitude was larger in the High compared to ADHD group, with this difference largest in the central region, while the Low group showed a tendency ( $p = .111$ ) towards larger Ne amplitude compared to the ADHD group.

Pe amplitude was larger in the High compared to ADHD group, although the effect was not localised to any particular region. Furthermore, a midline > lateral effect was largest in the central region in the High group and smallest in this region in the ADHD group.

#### **10.4.6.2 Simple versus Selective Inhibition**

Although there were no Group x Condition interactions for Ne amplitude, the component peaked later in the selective than simple condition in the ADHD group, while the Low group showed the opposite effect (i.e. Ne peaked later in the simple than selective condition).

Pe amplitude in the Low and High groups was larger in the simple than selective condition; the ADHD group showed the opposite effect. With respect to latency, Pe peaked later in the selective than simple condition in the ADHD group, while the High group showed the opposite effect.

**Table 10.6. A summary of ERP component amplitude and latency analyses and means results for successful stop trials. Notes: (1) all values are in  $\mu\text{V}$ .**

	Effect	Contrast	Effect Details	<i>F</i>	<i>p</i>
<b>Low vs. ADHD: Amplitude</b>					
Ne	G	ADHD vs. Low	-6.4 vs. -9.9	2.7	.111
Pe	G x C	Simple vs. Selective	ADHD: 4.4 vs. 9.3 Low: 8.5 vs. 2.8	5.9	.022
<b>Latency</b>					
Ne	G x C	Simple vs. Selective	ADHD: 51.2 vs. 92.0 ms Low: 91.4 vs. 73.4 ms	4.4	.045
<b>High vs. ADHD: Amplitude</b>					
Ne	G	ADHD vs. High	-6.4 vs. -11.9	6.8	.015
	G x S	c vs. f/p	ADHD: -8.0 vs. -5.7 High: -16.2 vs. -9.8	6.7	.016
Pe	G	ADHD vs. High	6.8 vs. 11.9	3.0	.079
	G x C	Simple vs. Selective	ADHD: 4.4 vs. 9.3 High: 14.2 vs. 9.7	4.7	.040
	G x L x S	cM to cL/R vs. f/pM to f/pL/R	ADHD: 10.7 to 6.3 vs. 8.2 to 5.4 High: 18.3 to 10.5 vs. 11.2 to 11.5	10.0	.004
<b>Latency</b>					
Pe	G x C	Simple vs. Selective	ADHD: 144.9 vs. 204.5 ms High: 238.7 vs. 185.0 ms	4.9	.035

## 10.5 Discussion

The aims of the present study were to examine the nature of the stop-signal inhibition process in adults with ADHD during simple and selective versions of the stop-signal task, relative to non-clinical Low and High impulsivity groups. It is generally accepted that response inhibition is deficient in children with ADHD, but evidence for a similar deficit in adults is scarce. Furthermore, in the previous study (Chapter 9) it was found that response processing was enhanced in the High compared to Low impulsivity group, and this effect was interpreted as underlying impulsive behaviour in this group. Therefore, it was hypothesised that if impulsivity in adults with ADHD reflected the extreme end of Eysenck's Impulsiveness trait (1993b), this group would show greater

response processing and larger Impulsiveness scores relative to the High group. Thus, poorer inhibitory control in adults with ADHD at the overt level of performance could be due to deficient response inhibition, over-active response processing, or both.

#### *10.5.1 Psychometric Measures*

Firstly, the ADHD group showed larger IVE Impulsiveness scores relative to the Low, but not the High, group. Therefore, in contrast to the notion that impulsivity in ADHD reflects the extreme end of the impulsiveness trait, scores in this group were not greater than those in the High impulsivity group. Furthermore, there were no significant between-group differences on the Venturesomeness or Empathy subscales. A similar pattern of findings was observed for the FrSBe, with larger scores in the ADHD compared to Low group on all but the Apathy subscales, while the High group showed similar scores to the ADHD group on all subscales. Together these findings show that the non-clinical highly impulsive subjects reported a similar frequency of impulsive traits and frontal executive dysfunctions as the adults with ADHD. In contrast, subjects in the Low group reported significantly lower degrees of these characteristics. Thus, in relation to impulsivity, the ADHD and High group were found to be behaviourally similar, as assessed via self-report measures. In contrast, the Low group was established as a “control” group not characterised by impulsivity or frontal executive problems, relative to adults with ADHD.

### *10.5.2 Performance Measures*

Although children with ADHD generally show slower responding (Dimoska et al., 2003; see Oosterlaan & Sergeant, 1996 for a review; Scheres, 2001 ), adults with ADHD may show faster (Aron et al., 2003a; Murphy, 2002) or similar response times to controls (Bekker et al., in press; Ossmann & Mulligan, 2003). In the present study, adults with ADHD did not differ in Go MRT or the likelihood of committing a choice error, relative to the two non-clinical groups, suggesting relatively intact response processing. Although children with ADHD consistently show a greater frequency of omission errors relative to controls, suggesting reduced attention to the task-at-hand (see Oosterlaan et al., 1998 for a review), adults with ADHD in the present study did not differ from the Low group on this measure. In contrast, the High group showed a greater probability of omission errors relative to the ADHD group, however, this effect probably reflects enhanced response processing in the High group (see also section 10.5.3 for ERP evidence), rather than an attentional deficit in the ADHD group.

With respect to the stopping component of the task, adults with ADHD showed a longer SSRT relative to the non-clinical groups, in line with previous studies (Aron et al., 2003a; Bekker et al., in press; Bekker et al., submitted; Murphy, 2002; Wodushek & Neumann, 2003; but see Epstein et al., 2001 for an exception), suggesting a slower inhibitory response. Furthermore, although overall inhibition probability did not differ between groups, the inhibition function was significantly flatter in the ADHD group compared to the non-clinical groups, and this effect remained even after applying the ZRFT correction (Logan & Cowan, 1984; Logan et al., 1984). A flat inhibition function can be due to a fast or variable go process, or a slow or variable inhibition process, or finally, an

inhibition process that is not triggered on every stop-signal trial (Logan, 1994).<sup>43</sup> As plotting inhibition probability as a function of ZRFT presumably removes effects related to go process and the latency of the inhibition process (Logan, 1994; but see Band et al., 2003b), the finding that the function remained flat even after this correction suggests that the inhibition process in adults with ADHD was triggered less frequently or was substantially more variable in latency, as well as slower (Logan, 1994).

What is immediately apparent about the inhibition function in the ADHD group is that inhibition probability did not decrease with an increase in stop-signal delay, as is assumed in a good fit of the data by the race model (Logan, 1994). In fact, at the longer stop-signal delays, where responses should not have been stopped easily, the ADHD group showed greater inhibitory success than the non-clinical groups. This effect suggests that adults with ADHD either omitted responses on a certain proportion of trials whether a stop-signal occurred or not, or alternatively, varied the latency of the go process greatly from trial-to-trial, thereby, increasing the likelihood of a successful stop (Logan, 1994). As inhibition probability was corrected for the number of omission errors (Tannock et al., 1989), this factor is discounted. Rather, large go process variability in the ADHD group is the likely cause (Logan, 1994; Oosterlaan et al., 1998). Although inhibition functions are meant to be brought into alignment when variability in the go process underlies a flatter inhibition function in a particular group, Band et al. (2003b) showed through simulated data sets that the ZRFT transformation does not completely remove the effect of go process variability. Therefore, increased go response variability in the ADHD group, relative to the

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<sup>43</sup> Two factors which contribute to the inhibitory outcome but which cannot be dissociated with the race model or with ERPs are the triggering rate and the variability of the latency of the inhibition process.



non-clinical groups, was probably a compensatory response to a deficient inhibition process, which resulted in comparable average inhibition probability between groups. Previously, it has been suggested that response variability is one of the most defining behavioural characteristics in ADHD (Hervey et al., 2004; Lazzaro et al., 1997; Oosterlaan et al., 1998; but see Ossmann & Mulligan, 2003 for an exception). It should be noted that correlations in the ADHD group revealed a significant relationship between selective SSRT and the FrSBe Executive Dysfunction subscale, although simple SSRT was not related to any scales. This finding supports the association between stop-signal inhibition and frontal lobe functions, specifically those related to the dorsolateral PFC, which the Executive Dysfunction subscale purports to measure (Stout et al., 2003).

### *10.5.3 Response Processing*

In contrast to the hypothesis that impulsivity in adults with ADHD may be mediated by a similar mechanism to the impulsiveness trait, that is, an over-active response process (Quay, 1988), the ADHD group showed significantly reduced amplitude and a longer onset of the stimulus-locked LRP, relative to the High group. Therefore, although these two groups did not differ in overt Go MRT, or in the frequency of impulsive traits, specific-side response preparation was reduced and delayed in the ADHD group. In fact, LRP amplitude did not differ between the ADHD and Low groups, supporting the notion that response processing in adults with ADHD is intact (Bekker et al., in press; Lijffijt et al., 2005; Ossmann & Mulligan, 2003), unlike in children with ADHD (Oosterlaan et al., 1998). However, an examination of the response-locked LRP revealed a shorter onset-to-RT interval in the ADHD compared to the two non-clinical groups, suggesting a shorter

duration of motor processing. These findings show that impulsivity in adults with ADHD is not mediated by the same underlying mechanism as the impulsiveness trait, that is, over-active response processing, although execution of the response once it has been selected may be faster in adults with ADHD.

A feature that was noted across groups for the stimulus-locked LRPs, particularly for successful and failed stop trials, was a positive-going deflection between 500 – 600 ms after the onset of the go stimulus. As positive-going activity reflects the activation of the incorrect response side (Coles et al., 1995), this deflection indicates that, on stop-signal trials, subjects may have activated the incorrect response, perhaps in an attempt to interrupt the execution of the correct response. This, however, is a tentative interpretation that requires further research beyond the scope of this thesis.

#### *10.5.4 Stop-signal Processing: Across Condition*

A main effect revealed reduced N1 amplitude in the ADHD compared to High, but not Low, group, with the largest difference occurring in the central region. Furthermore, findings showed relatively equipotential N1 amplitude across the lateral sites in the fronto-central region in the ADHD group, while amplitude showed a midline > lateral effect in the High group. These findings suggest that while the impulsiveness trait predisposed subjects in the High group to seek greater sensory stimulation from the stop-signal, manifested in a larger central N1 (Barratt, 1993; Eysenck, 1993a; Gray, 1987; Zuckerman, 1993; Zuckerman, 2002), impulsivity in the ADHD group was not associated with this “sensation-seeking” response. Although this particular effect does not reflect a deficiency in the ADHD group, a reduced N1 central maximum was found relative to the Low

impulsivity group. In line with Bekker et al. (submitted), this effect may reflect an early deficit in switching attention to the stop-signal, which may partly contribute to deficient inhibitory control.

A response inhibition deficit in adults with ADHD was supported in the present study as successful stop P3 was reduced in the ADHD compared to non-clinical groups (Aron et al., 2003a; Bekker et al., in press; Bekker et al., submitted; Fallgatter et al., 2005; Murphy, 2002; Wodushek & Neumann, 2003). This corresponds with the findings in Fallgatter et al. (2005), who showed a smaller Nogo-anteriorisation effect and a reduced fronto-central P3 for nogo trials in adults with ADHD in a cued go/nogo task, suggesting deficient activation of prefrontal inhibition or response control processes. Furthermore, in line with Bekker et al. (submitted), successful stop P3 was delayed in adults with ADHD relative to the High group. Together these findings support the notion of a deficient response inhibition process in adults with ADHD that was both slower (relative to the high group) and triggered less often. More specifically, as successful stop P3 may reflect the manifestation of inhibition at the last cortical site of inhibitory control (i.e. the primary motor cortex) (see Study III, Chapter 6)(Band & van Boxtel, 1999), reduced amplitude shows that fewer responses were stopped using the stop-signal inhibitory “brake” in this region. Rather, greater inhibitory success at the longer stop-signal delays in adults with ADHD may be attributed to a variable go process and reduced side-specific response preparation (i.e. reduced LRP amplitude).

The present P3 findings also provide further insight into the functional significance of the successful stop P3. In a previous study, this author suggested that P3 amplitude may reflect the outcome of inhibition, rather than the inhibitory action itself (Dimoska et al.,

2003). This interpretation was based on the findings that in studies which use the tracking method, P3 peak amplitude does not appear to differ between groups because inhibition probability is approximately 50 % for both groups (Bekker et al., submitted; Dimoska et al., 2003). However, in the present study, where stop-signal delay was set relative to each subject's MRT, although average inhibition probability did not differ between groups, successful stop P3 was reduced in the ADHD group. If P3 amplitude merely reflected the probability of a successful stop, there should be no difference between our groups. Rather, the successful stop P3 behaves more in line with the inhibitory action itself, probably reflecting the site or manifestation of inhibitory control (Study III, Chapter 6). Nevertheless, this opens an interesting avenue of research into the effect of setting stop-signal delay on P3 amplitude, and the implication of this is for underlying inhibition processes.

Although there were no significant effects for N2 mean amplitude when analyses were restricted to the frontal sites, there was a tendency towards a Group main effect with larger amplitude in the Low compared to ADHD group. However, there were no differences between the ADHD and High groups. Larger N2 amplitude may reflect a tendency in the Low group to stop a greater number of responses using the deliberate response selection process during early preparational stages of processing, relative to adults with ADHD (Study III, Chapter 6). However, as the effect failed to reach significance, we should not place too much emphasis on this effect.

An examination of slow-wave activity revealed a pattern of findings that corresponds with previous studies examining children with ADHD (Holcomb, 1986; Johnstone et al., 2003). That is, NSW and PSW amplitudes were reduced in the ADHD

group compared to the two non-clinical groups. Reduced fronto-central or central NSW activity in adults with ADHD may be associated with a general reduced preparedness of neurons to respond to incoming stimuli (Birbaumer et al., 1990; Rockstroh et al., 1992). In contrast, the PSW has been associated with inhibitory processing at both neuronal (Howard et al., 1980) and cognitive or behavioural levels (Kiefer et al., 1998; Podlesny et al., 1984). Johnstone et al. (2003) examined SW activity using the same low-pass filtering technique employed in this study and found globally reduced PSW in children with ADHD combined subtype, relative to controls. Holcomb et al. (1986) used the traditional method of quantifying mean slow-wave activity and found reduced positivity across child ADHD subtypes. Therefore, reduced PSW in adults with ADHD supports the notion that inhibitory activation was deficient in this group relative to the two non-clinical groups.

#### *10.5.5 Simple vs. Selective Inhibition*

Early in this thesis (Study 2, Chapter 5), selective inhibition was examined in a group of non-clinical adults to determine whether an additional stimulus discrimination to the stop-signal inhibitory response would be associated with delayed inhibitory processing and the activation of distinct inhibitory processes. Results revealed that stopping in healthy adults was performed with the same fast, and non-selective inhibition process in both simple and selective contexts. In the present study, simple and selective stopping was examined in adults with ADHD to determine whether selective inhibition may be associated with greater impairments and differential inhibitory processing, relative to simple inhibition. It was predicted that if adults with ADHD were unable to mediate performance in line with the increased cognitive complexity of the selective stop-signal

task, this would manifest in a longer SSRT and activation of a different inhibition process in the selective compared to simple condition, relative to the non-clinical groups.

Performance findings did not show any between-group differences in simple and selective inhibition. However, underlying ERP differences revealed that while the attention-related sensory process reflected in N1 did not differ between conditions in the ADHD group, amplitude was larger in the simple than selective condition in the two non-clinical groups. This finding shows that in adults with ADHD, stop-signals in the simple condition were not associated with greater attention than stop-signals in the selective condition. This is in contrast to previous findings in this thesis whereby a single stop-signal presented in a prevailing visual context may be more salient than a stop-signal presented amongst ignore-signals (Studies I and II, Chapters 4 and 5). Therefore, adults with ADHD showed impairment in modulating attention to the stop-signal between conditions.

The lack of significant Group x Condition effects for the N2 or P3 components suggests similar inhibitory processing between conditions in the ADHD group, relative to the non-clinical groups. However, examination of SW activity in the simple and selective conditions revealed a differential pattern between groups. Both the NSW and PSW components were larger in the selective compared to simple condition in the non-clinical groups, while this pattern was reversed in the ADHD group. The selective condition is generally more difficult than the simple condition in that it imposes a greater workload on neural processes (Study II, Chapter 5), which may explain the increased activation found in the non-clinical groups. In particular, PSW has been found to increase in amplitude with an increase in task difficulty (Kiefer et al., 1998; Kok, 1986). Therefore, the converse in the

ADHD group suggests atypical activation of neuronal excitation and inhibition between conditions (Birbaumer et al., 1990; Rockstroh et al., 1992), despite comparable performance to the non-clinical groups.

#### *10.5.6 Error-related Processing*

The ADHD group showed a reduced Ne compared to the High group, with this difference largest in the central region. It is unclear, however, whether this represents a deficiency in the ADHD group, or simply enhanced processing in the High group. However, the Low group showed a tendency towards larger Ne amplitude than the ADHD group suggesting that error or conflict-detection may have been impaired in the latter group (Liotti et al., 2005). Furthermore, a selective > simple effect for Ne peak latency in the ADHD group, relative to the small converse effect in the Low group, suggests a delay in error or conflict-detection in the more difficult stop-signal condition.

Pe amplitude, which has been associated with a compensatory response or the affective assessment of an error (Falkenstein et al., 2000; Nieuwenhuis et al., 2001), was larger in the High than ADHD group. Once again, this may or may not reflect a deficiency in the clinical group. Between conditions, Pe amplitude showed an interesting pattern of effects that appeared to mimic those observed for PSW on successful stop trials. That is, while the non-clinical groups showed greater Pe amplitude in the simple than selective condition, the ADHD group showed the converse effect. Overtom et al. (2002) found a reduced PSW in children with ADHD compared to controls in a simple stop-signal task, which they believed may have reflected, or contributed to, the Pe component. Therefore, an alternative (and tentative) interpretation of the PSW is that it reflects the evaluation of

the accuracy of a response (Falkenstein et al., 1994; Overtom et al., 2002), rather than inhibitory processes (Birbaumer et al., 1990; Howard et al., 1980; Kiefer et al., 1998; Podlesny et al., 1984; Rockstroh et al., 1992).

Together these findings suggest that error-detection processes in adults with ADHD are impaired, while proceeding compensatory processes show atypical activation, relative to non-clinical adults.

#### *10.5.7 Limitations*

A limitation of this experiment was the small number of subjects in each group. Had there been a greater number of subjects, certain effects, in particular those for the successful stop N2 and response-locked Ne, may have become significant. However, a small number of subjects was obtained because of the stringent criteria used to select adults with ADHD, including: (1) a current diagnosis of ADHD in adulthood, (2) fulfilling criteria on the ASRS-v1.1, and (3) no evidence of anxiety, depression or any other psychiatric problems. An issue that was apparent in the recruitment of subjects, as well as within the literature was the blur between subtypes in the adult form of ADHD, due to the decrease in overt expressions of hyperactivity with increasing age. Future research may benefit from attempting to delineate sub-threshold combined type individuals from “true” inattentive individuals, as well as replicating these findings with larger sample sizes.



### *10.5.8 Summary*

In summary, performance findings showed that average inhibition probability was not reduced in adults with ADHD compared to the non-clinical groups, however, this was due to increased response variability in this group as a means of compensating for an inhibition process that was triggered less frequently or was more variable in latency, as well as slower. Findings did not agree with the hypothesis that impulsivity in adults with ADHD may reflect the extreme end of Eysenck's Impulsiveness trait, as evidenced by the findings that: (a) Impulsiveness scores did not differ between the ADHD and High groups, and (b) response preparation was reduced (as opposed to greater), as manifested in reduced LRP amplitude, in the ADHD compared to High group. Rather, ERP findings suggested that impulsive stop-signal task performance in the ADHD group was the result of impaired stop-signal processing at both early sensory and later inhibitory stages. A reduced central N1 in adults with ADHD compared to the non-clinical groups suggested an impairment in switching attention to the stop-signal, which may have partly contributed to deficient and delayed inhibitory activation, itself reflected in a globally reduced (and delayed) successful stop P3. Between simple and selective conditions, findings showed that the ADHD group performed the two conditions similarly, although underlying slow-wave activity suggested atypical activation between conditions. Finally, evidence suggested delayed and deficient error-detection, as well as atypical activation of compensatory processing between simple and selective conditions in the ADHD group compared to the non-clinical groups. Together these findings suggest that, like children with ADHD, stop-signal processing is impaired in adults with the disorder.

The present study is the first to compare stop-signal task performance and ERPs between adults with ADHD and non-clinical adults who report low or high degrees of the impulsiveness trait. The findings are noteworthy in that they show that: (a) adults with ADHD, like children with the disorder, suffer from slower and deficient inhibitory processing, and (b) impulsivity in adults with ADHD may be considered to reflect a more dysfunctional form than that observed in self-reported high degrees of the impulsiveness trait, the latter of which may be linked with over-active response processing, rather than deficient response inhibition. It should be noted, however, that although the present findings did not support the notion of impulsivity in ADHD as reflecting the extreme end of the impulsiveness trait, this does not preclude a dimension view of impulsivity in ADHD, merely that the dimension is not related to current conceptualisations of Eysenck's Impulsiveness trait (Eysenck, 1993b).

## 11. Conclusions and Future Directions

The significance of response inhibition in the performance of everyday tasks (such as typing on a keyboard, or stopping your foot from pressing the accelerator pedal in a car) makes the examination of the response inhibition process, and the factors that affect its success, an important area of research. In particular, deficits in this process may lead to impulsive behaviours that are often considered socially inappropriate, or worse, functionally disabling (Logan, 1994). Within the laboratory, the stop-signal task has been implicated as one of the best measures of inhibiting an ongoing response because it is based on the race model, allowing an estimation of the latency of the unobservable inhibitory response, and a clear delineation of the events that evoke the “go” and “inhibition” responses (Logan, 1994; Quay, 1997; Schachar, Mota, Logan, Tannock, & Klim, 2000).

The success of the race model in examining response inhibition lies in its predictive utility and its generality, however, because hypotheses are couched in terms of reaction times, the model fails to consider the nature of the processes that underlie SSRT. A number of methods have been suggested to supplement the race model in investigating the nature of the stop-signal inhibition process (Logan, 1994; Van den Wildenberg, 2003). These include examining: (a) the relationship between stop-signal inhibition and other forms of inhibition, (b) brain processes underlying stop-signal inhibition, (c) within-subject manipulations of inhibitory processing, and (d) deficits in response inhibition. These methods were adopted for the primary aims of this thesis: to examine the nature of stop-signal inhibition and determine its electrophysiological correlate.

## 11.1 The Nature of Response Inhibition

### 11.1.1 General Performance

The primary aim of this thesis was to examine the nature of stop-signal inhibition. According to Logan and Cowan's (1984) executive-control theory, stop-signals have privileged access to the higher-order executive centre, which "houses" the inhibition process, enforcing and evaluating control over lower-level subsidiary processes. Response inhibition, therefore, should be able to be exerted at relatively high speeds (Band & van Boxtel, 1999). The findings in this thesis fit with this model as SSRT was relatively stable and fast across Studies I – IV, with an average of 234.3 ms and a range of 230 to 241 ms. A fast and stable SSRT is in line with previous findings (see Logan, 1994 for a review) and suggests that a single, global process may mediate response inhibition in healthy, young adults (Band & van Boxtel, 1999; Brunia, 1993; Brunia, 2003; Logan & Cowan, 1984).

In contrast, average inhibition probability (i.e. across stop-signal delays) was affected by a number of factors. Increased inhibition probability in the go/nogo compared to stop-signal task indicated that, despite slower response times in the latter task, the inhibition of an ongoing response was considerably more difficult than the inhibition of a prepared response (Study I). This was obviously a consequence of the stage at which go processing was stopped – stopping is more difficult the further the go response has progressed towards execution (Logan, 1994). Similarly, despite longer response times in the selective stop-signal task, inhibition probability was reduced relative to the simple stop-signal task, and when inhibition probability was plotted as a function of ZRFT, the inhibition functions aligned (Study II). Therefore, the difference in inhibitory control between these conditions was attributed to go process variability (Band, van der Molen, &

Logan, 2003; Logan, 1994; Logan & Cowan, 1984; Logan et al., 1984). In contrast, reduced inhibition probability in the fast compared to slow group was clearly due to the speed of the go process (Study IV). Finally, inhibition probability was reduced when stop-signals were rare compared to frequent (Study V), and this effect was not removed by plotting inhibition probability by ZRFT. Therefore, the inhibition process may have been triggered less often or been more variable when there was a bias towards responding. However, as the ZRFT transformation does not completely remove the effects of go process variability (Band et al., 2003), this could have also been a causal factor underlying poorer inhibitory control for rare stop-signals.

Therefore, the inhibition of an ongoing response was a stable and relatively fast response across studies, while inhibitory success appeared to be predominantly affected by the go process in healthy, young adults.

#### *11.1.2 Different Inhibition Tasks*

To examine the nature of response inhibition, firstly, the inhibition of an ongoing response in the typical stop-signal task was examined relative to other forms of inhibition. Inhibition of an ongoing response in the stop-signal task appeared to be associated with earlier and greater activation of inhibition processes, relative to the inhibition of a prepared response derived from the go/nogo task (Study I). This interpretation was based on the findings that ERPs for successful stop trials showed larger amplitudes and shorter peak latencies for all components, relative to nogo trials. It was suggested that these effects were probably the result of the context within which stimuli were presented. That is, a single auditory stimulus evokes a greater cortical response and is quicker to process than having to

discriminate between two auditory stimuli. This finding was in line with previous reports (van Boxtel, van der Molen, Jennings, & Brunia, 2001).

Inhibitory processing in the stop-signal task was relatively fast even when an additional stimulus discrimination was required to determine whether or not inhibition was required on a particular “signal” trial (Study II). Findings showed that, in contrast to nogo trials, the inclusion of the additional stimulus discrimination to the stop-signal inhibitory response in the selective stop-signal task did not delay inhibitory processing. Rather, similar SSRT and ERP latencies between simple and selective conditions suggested that healthy adults adopted the more efficient inhibition strategy of “stop first, think later” in the selective stop-signal task, and this was probably due to the fact that an *ongoing* response requires urgent inhibitory control. Subjects appeared to stop go processing to the detection of any auditory stimulus before complete identification, and then continued stimulus evaluation, re-engaging the go process if the stimulus was identified as an ignore-signal. Although this strategy resulted in slower responses, it is overall more efficient for inhibitory control because, unlike deciding between a left or right hand response (Gratton, Coles, Sirevaag, & Donchin, 1988; Smid, Fiedler, & Heinze, 2000), incorrect inhibitory activation can be easily subsequently corrected.

An examination of the topographic distribution of ERP components allowed an insight into the spatial characteristics of inhibitory processing in different inhibition contexts. In line with imaging evidence that shows how inhibition manifests differently in the go/nogo and stop-signal tasks (Rubia et al., 2001), and more generally between different inhibition tasks (Garavan, Ross, & Stein, 1999; Mostofsky et al., 2003), all ERP components showed differential topographic distribution across the scalp (Study I). In

particular, nogo P3 showed a frontal maximum and was lateralised to the left hemisphere, corresponding to a left-frontal source found by previous studies (Bokura, 2001; Kiefer, Marzinzik, Weisbrod, Scherg, & Spitzer, 1998; Kok, 1986; Roberts, Rau, Lutzenberger, & Birbaumer, 1994). Although a right hemispheric specialisation has been implicated for stop-signal inhibition in brain imaging (Rubia et al., 2001) and lesion studies (Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003b), successful stop P3 had a midline-centro-parietal maximum. Notably, brain imaging reflects the activation of processes across a large temporal epoch, while ERPs provide enhanced temporal information that can dissociate early sensory and late inhibitory processes. Together these findings supported the notion of differential inhibitory processing between the two tasks, but provided only partial support for Rubia et al.'s (2001) hemispheric dissociation of left-nogo and right-stop-signal inhibition.

The focus of activity on left-frontal processes in the go/nogo task (Bokura, 2001; Casey, Castellanos, Giedd, & Marsh, 1997; Garavan et al., 1999; Kiefer et al., 1998; Konishi et al., 1999), as opposed to the midline, centro-parietal distribution for successful stop P3 in the stop-signal task (Kok, Ramautar, de Ruiter, Band, & Ridderinkhof, 2004; Ramautar et al., 2004) was interpreted in line with Band and van Boxtel's (1999) triad conceptualisation of inhibition as reflecting an agent, site and manifestation. One of the key differences identified between the go/nogo and stop-signal tasks was that inhibition is evoked at differential stages of response processing (see sections 1.9 and 3.6.1). Therefore, the left-frontal maximum for nogo P3 was interpreted as reflecting response selection or modulation at early preparational stages of processing, rather than inhibitory control per se (Rubia et al., 2001). In contrast, as responses in the stop-signal task are typically stopped at

more advanced stages of processing, the midline, centro-parietal maximum of the successful stop P3 was believed to reflect the manifestation of inhibitory control at, or near, the motor or premotor cortex, believed to be the last cortical site of inhibition (Band & van Boxtel, 1999; Brunia, 1993; Brunia, 2003). Therefore, the different topographic distribution of P3 between go/nogo and stop-signal tasks most likely reflected inhibition acting on different stages of go processing (Band & van Boxtel, 1999), that is, the site or manifestation of inhibition, rather than the agent.

Despite the additional stimulus discrimination in the selective stop-signal task, the strategy of “stop first, think later” allowed responses to be stopped using a similar inhibition process to the simple stop-signal task (Study II). ERPs revealed some evidence that the inhibition process was engaged differentially – for example, the broader distribution of stop N2 in the selective condition, as opposed to the frontal focus in the simple condition, which was believed to reflect the additional stimulus discrimination processes and working memory load. However, these processes occurred in parallel with inhibitory activation and, ultimately, did not affect the manner in which the response was stopped, as reflected in similar distribution across the sagittal region for stop P3. Therefore, in line with de Jong et al. (1995), similar SSRT, ERP peak latencies and the topographic distribution of stop P3 between simple and selective conditions suggested that a similar fast, non-selective, inhibition process was evoked in both conditions.

Together these findings show that (a) inhibiting responses at different stages of processing manifests differentially in the ERP, and (b) subjects adopted a fast inhibitory strategy of “stop first, think later” in the stop-signal task, due to the urgency associated with stopping a response that has already been triggered.



### *11.1.3 Response Styles*

It has been shown that increasing stop-signal probability encourages a bias towards inhibition by modulating the response process. This results in an increase in response time and a concurrent decrease in the probability of a failed stop (Lappin & Ericksen, 1966; Logan & Burkell, 1986; Logan et al., 1984; Ollman, 1973; Ramautar et al., 2004), although there appears to be no effect on SSRT (Logan & Burkell, 1986; Logan et al., 1984; Ramautar et al., 2004). In contrast, van den Wildenberg et al. (2003) suggested that inducing a tonic state of inhibition resulted in more forceful responses that were more difficult to inhibit, which in turn, prolonged the inhibitory response. Therefore, there was conflicting evidence as to whether the parameters of the response affected inhibitory processing. However, Logan's executive-control theory (1984) states that changes in top-down support are applied at higher levels than the subsidiary processes, therefore, the inhibition process should be unaffected by the characteristics of the go response. In agreement with this notion, SSRT was unaffected by response speed (Study III) or manipulations of response preparation (Study IV). Section 11.4 discusses the effects of response styles on underlying processes in relation to the clarification of the functional roles of stop-signal ERPs (see below).

### *11.1.4 Response Inhibition and Impulsivity*

The final aim of this thesis was to examine the nature of response inhibition in populations believed to be deficient in this process. Impulsivity and response inhibition

have been intrinsically linked in the literature (Logan et al., 1997; Schachar & Logan, 1990), despite the fact that impulsivity is a multifaceted construct (e.g. Barratt, 1993; Barratt & Patton, 1983; Carrillo-de-la-Pena, Otero, & Romero, 1993; Horn, Dolan, Elliott, Deakin, & Woodruff, 2003). Although some studies have shown a positive correlation between personality-based measures of impulsiveness and stop-signal inhibitory performance (Gorlyn, Keilp, Tryon, & Mann, 2005; Logan et al., 1997; Marsh, Dougherty, Mathias, Moeller, & Hicks, 2002; Vigil-Colet & Codorniu-Raga, 2004; Wodushek & Neumann, 2003), the findings in this thesis suggested that high degrees of the impulsiveness trait did predispose subjects to poorer inhibitory control (Study V). Extreme low and high scorers on Eysenck's Impulsiveness subscale (1993b), pre-selected from a large sample pool, did not show any differences in stop-signal task performance, which agreed with the findings from a previous study that also examined extreme low and high impulsivity groups (Rodriguez-Fornells, Lorenzo-Seva, & Andres-Pueyo, 2002), and more generally, with studies showing that personality and laboratory-based measures of impulsivity are uncorrelated (see Barratt & Patton, 1983 for a review; Carrillo-de-la-Pena et al., 1993; Gerbing, Ahadi, & Patton, 1987; White et al., 1994; Zaparniuk & Taylor, 1997). Therefore, a deficit in stop-signal inhibition did not underlie the impulsiveness trait.

Underlying quantitative differences in processing between the Low and High groups showed that highly impulsive subjects had an over-active response process (Eysenck, 1993a; Gray, 1987), sought greater sensory stimulation from stop-signals (Zuckerman, 1993), and activated inhibitory processing to a greater extent to counteract response processing (Horn et al., 2003), relative to the low impulsivity group. Furthermore, event-related SW activity (0.01 – 2 Hz) suggested faster neuronal preparation and enhanced

neuronal defacilitation in high compared to low impulsivity groups. Therefore, subjects who reported high degrees of the impulsiveness trait showed a compensatory response of increased inhibitory activation to counteract an impulsive response style, resulting in comparable overt performance to low impulsivity subjects. The activation of compensatory responses resulting in comparable performance is a phenomenon that has also been found in children (Johnstone & Barry, 1996; Karayanidis et al., 2000) and adults with ADHD (Bush et al., 1999).

Although highly impulsive non-clinical subjects reported a similar degree of impulsive traits and frontal lobe dysfunctions as adults with a current diagnosis of ADHD, inhibitory performance and underlying processes differed significantly between these two groups. Specifically, in contrast to the notion that impulsivity in adults with ADHD may reflect the extreme end of the impulsiveness trait (see generally Sonuga-Barke, 1998), adults with ADHD showed reduced, rather than greater, specific-side response preparation, as reflected in reduced LRP amplitude. Instead, LRP amplitude was similar to that of the low impulsivity group. Furthermore, performance findings showed similar Go RT. Therefore, go processing appeared intact in adults with ADHD, in line with some studies (Bekker et al., in press; Ossmann & Mulligan, 2003), but not with those that have found faster RT relative to controls (Aron, Dowson, Sahakian, & Robbins, 2003a; Murphy, 2002).

Poorer inhibitory control in adults with ADHD, as revealed by a longer SSRT and flatter inhibition function relative to the two impulsivity groups, supported the notion that response inhibition is impaired in adults (Aron et al., 2003a; Barkley et al., 1996; Bekker et al., in press; Epstein et al., 1998; see Lijffijt, et al., 2005 for a review of stop-signal studies) as in children (see Oosterlaan, Logan, & Sergeant, 1998 for a review). Furthermore, the

inhibition function did not fit the race model's assumption of decreased inhibition probability with increasing stop-signal delay, suggesting that go process variability may have been substantially greater in the ADHD than non-clinical groups. ERPs also suggested impaired stop-signal processing with the ADHD group showing deficits in switching attention to the stop-signal (central N1) (Bekker et al., submitted) and reduced, as well as delayed, inhibitory activation (successful stop P3) (Fallgatter et al., 2005) in relation to the two impulsivity groups. Therefore, although adults with ADHD showed comparable average inhibition probability to the two non-clinical groups, response inhibition was deficient and slower, and this was partly due to early sensory processing deficits (Bekker et al., submitted).

The examination of simple and selective inhibition in adults with ADHD, relative to non-clinical adults, revealed that inhibitory performance and processing between simple and selective conditions generally did not differ from non-clinical adults. However, enhanced central N1 amplitude in the simple compared to selective condition was found for non-clinical adults, with this effect reduced in the ADHD group, suggested that the degree of attentional switching to stop-signals did not differ between conditions for the latter group, while the non-clinical groups showed enhanced processing in the simple condition. Between-condition differences in the inhibition-related components, successful stop N2 and P3, did not differ between groups. Thus, adults with ADHD showed similar inhibitory processing in the selective condition to the non-clinical groups. However, when SW activity was examined separately from the typically quantified ERP components, an atypical pattern of findings was observed between conditions. This finding is interesting because it showed that although adults with ADHD may perform similarly to non-clinical

adults, underlying activity may be atypical (Bush et al., 1999; Johnstone & Barry, 1996; Karayanidis et al., 2000). Furthermore, it suggests that underlying processing differences may be obscured when higher frequencies are included in the ERP, and are therefore, best observed by examining SW activity through the low-pass filtering technique (Johnstone & Barry, 1999; Johnstone, Barry, & Dimoska, 2003).

Together these findings suggest that deficiencies in the stop-signal-type inhibitory processing may manifest in a more dysfunctional form of impulsivity than that reflected in the impulsiveness trait.

## **11.2 Electrophysiological Correlates of Response Inhibition**

A further aim of this thesis was to examine the functional roles of stop-signal ERPs in order to determine the correlate of the stop-signal inhibition process. The auditory-evoked N1 peaked, on average, 135 ms after the onset of the stop-signal and showed a midline, fronto-central maximum for successful stop trials, which was typically reduced for failed stop trials, across studies. A number of sources were identified as contributing to the stop N1 by a PCA (Study IV) in line with previous reports (Näätänen & Picton, 1987). A larger central N1 was found for successful compared to failed stop trials (Studies I and II) and in conditions with a greater inhibition probability (Study III), while N1 typically peaked later for failed compared to successful stop trials. These findings are in accord with the notion that N1 reflects the initial extraction of information from the sensory analysis of the stimulus and, more generally, the amount of attention directed towards a stimulus (Näätänen & Picton, 1987). Although the N1 was not related to the inhibition process per se, it was found that early sensory discrimination at this latency was essential for a

subsequent successful inhibition as it assured further central processing of the stop-signal (Bekker et al., 2005a). Therefore, the findings in this thesis support the notion that the decision to inhibit begins early in processing (Filipovic et al., 2000; Naito & Matsumura, 1996; Sasaki et al., 1993; Sasaki et al., 1989).

Factors which appeared to affect N1 amplitude, and the subsequent successful of inhibition, was the overall salience of the stop-signal within the context of other stimuli. For example, stop-signals in the simple stop-signal task may have been more salient and attracted more attention because they were the only auditory stimulus, as compared to nogo stimuli in the go/nogo task (Study I) or stop-signals in the selective stop-signal task (Study II), where the inhibition stimulus was presented in relation to another auditory stimulus. However, larger N1 amplitude was not always associated with a successful stop. In Study IV, where global stimulus probability was a factor, rare stop-signals were associated with larger N1 amplitude in the midline and central regions, relative to more frequent stop-signals, despite inhibitory success being reduced. Furthermore, N1 amplitude was larger in the High compared to Low impulsivity group (Study V) suggesting enhanced stop-signal processing, although inhibitory performance was comparable between groups. Therefore, while efficient stop-signal processing at the N1 latency range appears to be essential for a subsequent inhibition, stop N1 appeared to be modulated by (a) attention (or the salience of the stop-signal), (b) global stimulus probability, and (c) the impulsiveness trait.

Stop P2 was examined in Study I, but, because it was so difficult to identify and quantify, was excluded from subsequent analyses. Likewise, stop N2 was not present in all participants. Therefore, mean amplitude in the 200 – 250 ms latency range was quantified to examine activity in this critical period of stop-signal processing (Logan, 1994). A PCA

showed that the mean amplitude in this latency range reflected the activity of a frontal N2, although the stop P3 overlapped activity in the centro-parietal region (Study IV). Stop N2 showed a frontal (Studies I and II) or fronto-central (Study III) maximum and peaked approximately 205 – 235 ms after the onset of the stop-signal. In Study III, where the response inhibition hypothesis was examined for stop N2 through a comparison of fast and slow RT groups, and it was predicted that faster responses would be associated with *greater* or *faster* inhibitory activation, N2 was actually larger in the slow group. Furthermore, the response conflict hypothesis was examined through a comparison of stop N2 and response-locked Ne, which revealed a centrally-maximal midline > lateral effect for Ne that was reduced for stop N2. As the topographic distribution of a component provides an insight into its underlying sources (Donchin et al., 1978; Picton et al., 2000; Spencer et al., 2001), the finding of different topographic distributions is in contrast to the response conflict hypothesis, which suggests that N2 and Ne reflect different manifestations of the *same* underlying process in the ACC (Donkers & van Boxtel, 2004; Nieuwenhuis et al., 2003; van Veen & Carter, 2002). Together these findings suggested that stop N2 did not reflect either the stop-signal inhibition process or response conflict.

Larger N2 amplitude in the slow RT group, who also showed greater inhibition probability, however, was in line with a previously similar finding (Falkenstein et al., 1999), and suggested a general role in response control. Furthermore, the previous association between N2 and the dorsolateral PFC (Kiefer et al., 1998; Mathalon et al., 2003; Rubia et al., 2003; Swainson et al., 2003), which plays a role in the preparation and selection of responses (Garavan et al., 2000; Rowe et al., 2000; Rubia et al., 2003), suggested that stop N2 may reflect the deliberate selection of the inhibitory response (Kok,

1986; Kopp, 1996; Swainson et al., 2003) during the early stages of response preparation and selection in “medial” motor loop outlined by Goldberg (1985). If, however, responses were too fast, this process may have been “by-passed” in favour of an urgent inhibitory brake (see stop P3 below).

The auditory-evoked P3 peaked, on average, 335 ms after the onset of the stop-signal and showed a midline, centro-parietal maximum for successful stop trials and a central maximum for failed stop trials, across studies. Across studies, findings suggested that the successful stop P3 behaved in line with the stop-signal inhibition process (e.g. Bruin et al., 2001; de Jong et al., 1990; Falkenstein et al., 2002; Kiefer et al., 1998). For example, successful stop P3 amplitude was larger in conditions where inhibition involved an urgent inhibitory brake, such as for successful stop compared to nogo trials (Study I), for fast compared to slow responders (Study III), and in impulsive adults (Study V), but was impaired in adults with ADHD who showed poorer inhibitory control (Study VI).

A number of researchers have suggested that the stop P3 occurs too late to reflect the action of the inhibition process (Bekker et al., in press; Falkenstein et al., 1999). This is typically based on the premise that there is a 100 ms transmission delay between process onset and effect. Therefore, because stop P3 onset is typically around 150 ms and SSRT is around 230 ms, this suggests that the response is stopped before the process reflected in P3 can exert its influence (Bekker et al., 2005a). However, in line with the triad conceptualisation of inhibition (Band & van Boxtel, 1999), although the response may be stopped at a site prior to P3’s “influence”, the manifestation of this inhibitory effect may occur after the site, and therefore, be reflected in successful stop P3. Furthermore, successful stop P3 is believed to reflect activity near or in the motor or premotor cortex



(Kok et al., 2004; Ramautar et al., 2004), and as inhibition in the stop-signal task typically occurred at later stages of response processing, larger central (Study V) or centro-parietal successful stop P3 (Studies I – IV) may reflect the manifestation of urgent inhibitory control in this region, that is, the last cortical site of inhibition (Band & van Boxtel, 1999; Brunia, 1993; Brunia, 2003).

The functional dissociation between N2 and P3 observed throughout this thesis are in line with the theory of distinct inhibition processes whose activation depends upon the urgency of the inhibitory requirement (Garavan et al., 2002). Although greater negativity in the 200 latency range may be associated with the activation of a slow, deliberate inhibition process, greater stop P3 may reflect an urgent, inhibitory brake. The frontal maximum of the N2 corresponds with the PFC, whose function has been associated with the selection (Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000; Rubia et al., 2003) or switching of responses (Garavan et al., 2000). On the other hand, the successful stop P3 is believed to reflect activity from near or in the primary motor cortex region (Kok et al., 2004), therefore, greater amplitude of this component in subjects who are more likely to stop fast responses with an urgent inhibitory brake fits well with the notion that the primary motor cortex is the last site of inhibition (Band & van Boxtel, 1999). Although ERPs are limited in their utility for determining underlying neural sources, these findings also lend support for Brunia's (1997; 2005) inhibition theory of a slow versus fast inhibitory route.

With respect to failed stop trials, N2 and P3 were found to reflect the aggregate of stop-signal and error-related response processing (Study III). Therefore, the commonly reported enhancement of N2 amplitude for failed trials (Kok et al., 2004; Ramautar et al., 2004; van Boxtel et al., 2001) was attributed to error-related negativity overlapping the stop

N2 in this latency range, in line with Kok et al. (2004). Also of particular note is that these findings suggested that the typically found enhancement of P3 amplitude on successful compared to failed trials (Bekker et al., submitted; de Jong et al., 1990) is possibly a by-product of error-related negativity (Ne) on failed trials rather than inhibition-related positivity on successful trials. Furthermore, the comparison of stimulus- and response-locked ERPs for failed stop trials revealed a similar behavioural pattern between failed stop N2 and Ne, as well as between failed stop P3 and Pe, however, there were distinct differences in topographic distribution which suggested that error-related processes were best examined in the response-locked ERP averages (Studies IV and V).

Findings reported here suggest that auditory ERPs to stop-signals do not simply reflect inhibitory (or error-related) processing (Study IV). Because auditory stop-signals are typically novel events in a prevailing visual context, the ERPs also reflected “oddball” effects. That is, ERP amplitudes were enhanced by the low probability of the stop-signal. Findings showed a larger N1/P3 complex for rare compared to frequent stop-signals, which has previously been interpreted as reflecting increased inhibitory activation to counteract a bias towards responding (Ramautar et al., 2004). However, the same enhancement for rare compared to frequent trials was observed for ignore-signals, which suggested that modulations in component amplitude did not reflect varying inhibitory requirements, but rather, oddball effects. Therefore, stop-signal ERPs reflect the aggregate activity of inhibitory processing and probability-related effects.

In sum, the findings in this thesis show that the successful inhibition of an ongoing response in the stop-signal task begins with the efficient early sensory processing of the stop-signal (N1) and ends with the site or manifestation of inhibition near or in the motor or

premotor cortex, that is, the last cortical site of inhibition (successful stop P3). However, a participant may deliberately “select” the inhibitory response (successful stop N2) if responses are still in preparational stages when the instruction to inhibit is presented. Finally, failed stop trials reflect the aggregate of stop-signal and error-related activity, but stop-signal ERPs across successful and failed trials reflect the aggregate of inhibitory (or error-related) processing and probability-related oddball effects.

### **11.3 Conclusions**

The findings presented here show that response inhibition is a fast, urgent action when the response to be stopped has already been prepared or triggered, as it is in the stop-signal task. The latency of inhibition remained unaffected by the parameters of the go process and by manipulations of inhibition difficulty. Healthy subjects typically adopted the efficient inhibition strategy of “stop first, think later”. ERP evidence suggested that the site of inhibition may vary along the response trajectory and manifest differentially on the scalp surface. In particular, stopping a response in early preparational stages may be associated with a site in the frontal region (successful stop N2), although once the response has been prepared, a response may be stopped closer to the last cortical site of inhibition, that is, the primary motor cortex (successful stop P3). However, ERP findings show that a successful stop is partially dependent upon the efficient switching of attention to the stop-signal at early stages of sensory processing (stop N1), while processing on failed stop trials was found to reflect the aggregate activity of stop-signal and error-related response processing. Finally, an examination of stopping in “impulsive” populations revealed that

deficiencies in the stop-signal inhibition process were related to the more dysfunctional (clinical) form of impulsivity, rather than underlying impulsive behaviours in general.

#### **11.4 Future Directions**

A number of avenues for future research into response inhibition are generated from the findings presented here. Although the comparison of the simple stop-signal and go/nogo tasks provided an insight into processing differences between the inhibition of ongoing and prepared responses, future research should aim to examine the *interaction* between stop-signal inhibition and other forms of inhibition using ERPs. Recently, researchers have begun to investigate the interaction between stop-signal inhibition and inhibition of distractor stimuli (Ridderinkhof et al., 1999), or the inhibition of incompatible responses in stimulus-response compatibility tasks (e.g. the flanker and stroop tasks) (Verbruggen, Liefoghe, & Vandierendonck, 2004). However, there are no studies, to-date, that have examined the effect of these interactions on associated ERP components. Similarly, there is a need for research examining the effect of manipulating the stop-signal inhibitory response using ERPs. This thesis examined selective inhibition when the stimulus discrimination was directly related to the processing of the stop-signal, however, selective inhibition may also be investigated by making the decision to inhibit dependent upon primary task stimulus discrimination (see section 1.7.2). As these two designs may be associated with different inhibition processes and strategies, future research should also provide a within-participant ERP examination of simple and selective inhibition using the latter design.

It was reported that failed stop trials may not primarily reflect inhibitory processing as was previously believed, but rather, appear to be overlapped by response-related processes. Future research should, therefore, aim to recognise that comparisons of successful and failed stop trials may not be informative of inhibitory processing. That is, the differences in successful and failed trials observed for N2 and P3 amplitudes do not necessarily reflect a difference in inhibitory activation, but rather, are a by-product of Ne component overlap. Furthermore, as stop-signal ERPs may be confounded by the response to a rare event, future research may benefit from attempting to dissociate probability-related oddball effects from true inhibitory processing through careful task design.

With respect to impulsivity, although it was found that a high degree of the impulsiveness trait, as measured by Eysenck's Impulsiveness subscale (1993b), was not associated with deficient stop-signal inhibition, this does not discount the association between deficient response inhibition and the impulsiveness trait entirely. Future research should examine a different combination of laboratory and personality measures of impulsivity to provide further clarification on the definition and causality of this construct, as well as its association with cognitive deficits.

On a related topic, it should be noted that although the present findings did not support the notion of impulsivity in ADHD as reflecting the extreme end of the impulsiveness trait, this does not preclude a dimension view of impulsivity in ADHD, merely that the dimension is not related to current conceptualisations of Eysenck's Impulsiveness trait (Eysenck, 1993b). Future research should aim to examine the factor structure of ADHD-related impulsivity symptoms across varying degrees of severity using factor analysis techniques to determine the presence of a latent trait, or several interacting

traits. Furthermore, future research into ADHD should aim to provide an integrated view of motivational and executive forms of inhibition in underlying impulsivity. Finally, an issue that was apparent in the review of ADHD literature was the blur between subtypes in the adult form of the disorder, due to the decrease in overt expressions of hyperactivity with increasing age. Future research may benefit from attempting to delineate sub-threshold combined type individuals from “true” inattentive individuals.

Although there is some understanding of the neural mechanisms mediating response inhibition from brain imaging studies, ERP components provide enhanced temporal resolution, allowing a dissociation between individual stages of processing. However, researchers are only beginning to understand the functional roles of ERPs in the stop-signal task. The present findings are the first attempt to incorporate current neuropsychological concepts of inhibition in the interpretation of ERP effects. Future research should aim to expand on the findings presented in this thesis by combining ERP and brain imaging techniques.

### **11.5 A Final Thought**

Although impulsivity and poor inhibitory control have been put forward as relatively dire attributes that negatively affect behaviour and cognitive functioning, they may still be useful when this strategy is appropriate to the context (Dickman, 1990). For example, being able to slam your foot on the brake quickly if a dog runs in front of you whilst driving, typically, demands an immediate action. One can imagine the tragic consequence if an individual responds slowly, or inhibits the response, in order to fully examine the possible outcomes of each potential course of action. Therefore, the positive

side of impulsivity and poor inhibitory control must be acknowledged. Nevertheless, efficient responding to the ever-changing requirements of the external environment or our own internal directions involves a complex interaction of both *activation* and *inhibition* processes. Throughout this thesis, healthy participants demonstrated that they could manipulate both of these processes accordingly, in order to adopt a particular response style or strategy that would suit the purposes of the task imposed upon them. In most cases, they chose the more efficient strategy that resulted in the greatest overall inhibitory success. However, even in cases where participants were predisposed to impulsive response styles, whether this be due to personality traits or other factors, they still had the ability to compensate through modulations of the inhibition process. In contrast, adults with ADHD, who did not have this facility at their disposal, showed significant inhibitory control problems. Thus, this thesis underscores the essential and adaptive nature of the response inhibition process and shows that, while action is an important aspect of our society, we also need to remember to simply... *stop*....

## 12. References

- Adler, L. A., & Cohen, L. (2003, 26 June 2003). *Screening adults for Attention-deficit/Hyperactivity Disorder (ADHD)*. Retrieved January 29, 2004, from [http://www.medscape.com/viewprogram/2499\\_pnt](http://www.medscape.com/viewprogram/2499_pnt)
- Allison, T., Wood, C. C., & McCarthy, G. (1986). The central nervous system. In M. G. H. Coles, E. Donchin & S. W. Porges (Eds.), *Psychophysiology: Systems, processes, and applications* (pp. 5-25). New York: Guilford.
- Aron, A., Robbins, T., & Poldrack, R. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, 8(4), 170-177.
- Aron, A. R., Dowson, J. H., Sahakian, B. J., & Robbins, T. W. (2003a). Methylphenidate improves response inhibition in adults with attention-deficit/hyperactivity disorder. *Biological Psychiatry*, 54(12), 1465-1468.
- Aron, A. R., Fletcher, P. C., Bullmore, E. T., Sahakian, B. J., & Robbins, T. W. (2003b). Stop-signal inhibition disrupted by damage to right inferior frontal gyrus in humans. *Nature Neuroscience*, 6(2), 115-116.
- American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders*. (4<sup>th</sup> ed.). Washington, D.C: Author.
- American Psychiatric Association. (2000). *Diagnostic and statistical manual of mental disorders*. (4<sup>th</sup> ed., Text Revision). Washington, D.C: Author.
- Avila, C., Cuenca, I., Félix, V., Parcet, M. A., & Miranda, A. (2004). Measuring impulsivity in school-aged boys and examining its relationship with ADHD and ODD ratings. *Journal Of Abnormal Child Psychology*, 32(3), 295-304.
- Avila, C., & Parcet, M. A. (2001). Personality and inhibitory deficits in the stop-signal task: The mediating role of Gray's anxiety and impulsivity. *Personality & Individual Differences*, 31(6), 975-986.
- Bachorowski, J. A., & Newman, J. P. (1985). Impulsivity in adults: motor inhibition and time-interval estimation. *Personality and Individual Differences*, 6(1), 133-136.



- Band, G. P. H. (1997). *Preparation, adjustment, and inhibition of responses*. Unpublished Doctoral dissertation, University of Amsterdam, Amsterdam, Netherlands.
- Band, G. P. H., & Kok, A. (2000). Age effects on response monitoring in a mental-rotation task. *Biological Psychology*, 51(2-3), 201-221.
- Band, G. P. H., Ridderinkhof, K. R., & van der Molen, M. W. (2003a). Speed-accuracy modulation in case of conflict: the roles of activation and inhibition. *Psychological Research*, 67, 266-279.
- Band, G. P. H., & van Boxtel, G. J. M. (1999). Inhibitory motor control in stop paradigms: Review and reinterpretation of neural mechanisms. *Acta Psychologica*, 101, 179-211.
- Band, G. P. H., van der Molen, M. W., & Logan, G. (2003b). Horse-race model simulations of the stop-signal procedure. *Acta Psychologica*, 112, 105-142.
- Band, G. P. H., van der Molen, M. W., Overtoom, C. C. E., & Verbaten, M. N. (2000). The ability to activate and inhibit speeded responses: Separate developmental trends. *Journal of Experimental Child Psychology*, 75(4), 263-290.
- Banquet, J. P., Renault, B., & Lesevre, N. (1981). Effect of task and stimulus probability on evoked potentials. *Biological Psychology*, 13, 203-214.
- Barkley, R., & Gordan, M. (2000). Research on comorbidity, adaptive functioning, and cognitive impairments in adults with ADHD: Implications for a clinical practice. In S. Goldstein & A. T. Ellison (Eds.), *Clinician's guide to adult ADHD* (pp. 46-83). San Diego: Academic Press.
- Barkley, R. A. (1990). *Attention deficit hyperactivity disorder: A handbook of diagnosis and treatment*. New York: Guilford Press.
- Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, 121(1), 65-94.
- Barkley, R. A. (1998). *Attention Deficit Hyperactivity Disorder: A handbook of diagnosis and treatment*. New York: Guilford.

- Barkley, R. A., & Gordan, M. (2002). Research on comorbidity, adaptive functioning, and cognitive impairments in adults with ADHD: Implications for a clinical practice. In S. Goldstein & A. T. Ellison (Eds.), *Clinician's guide to adult ADHD*. San Diego: Academic Press.
- Barkley, R. A., Murphy, K., & Kwasnik, D. (1996). Psychological adjustment and adaptive impairments in young adults with ADHD. *Journal of Attention Disorders*, 41-54.
- Barkley, R. A., Murphy, K. R., & Bush, T. (2001). Time perception and reproduction in young adults with Attention Deficit Hyperactivity Disorder. *Neuropsychology*, 15(3), 351-360.
- Barratt, E. S. (1959). Anxiety and impulsiveness related to psychomotor efficiency. *Perceptual and Motor Skills*, 9, 191-198.
- Barratt, E. S. (1983). The biological basis of impulsiveness: the significance of timing and rhythm disorders. *Personality and Individual Differences*, 4(4), 387-391.
- Barratt, E. S. (1987). Impulsiveness and anxiety: Information processing and electroencephalograph topography. *Journal of Research in Personality*, 21(4), 453-463.
- Barratt, E. S. (1993). Impulsivity: Integrating cognitive, behavioural, biological, and environmental data. In W. G. McCown, J. L. Johnson & M. B. Shure (Eds.), *The impulsive client: Theory, research, and treatment* (pp. 151-183). Washington, DC: American Psychological Association.
- Barratt, E. S., & Patton, J. H. (1983). Impulsivity: Cognitive, behavioural, and psychophysiological correlates. In M. Zuckerman (Ed.), *Biological basis of sensation seeking, impulsivity, and anxiety*. Hillsdale, NJ: Erlbaum.
- Barratt, E. S., Pritchard, W. S., Faulk, D. M., & Brandt, M. E. (1987). The relationship between impulsiveness subtraits, trait anxiety, and visual N100 augmenting/reducing: A topographic analysis. *Personality and Individual Differences*, 8(1), 43-51.
- Barratt, E. S., Stanford, M. S., Kent, T. A., & Felthous, A. (1997). Neuropsychological and cognitive psychophysiological substrates of impulsive aggression. *Biological Psychiatry*, 41(10), 1045-1061.

- Bayliss, D. M., & Roodenrys, S. (2000). Executive processing and attention deficit hyperactivity disorder: An application of the supervisory attentional system. *Developmental Neuropsychology*, 17(2), 161-180.
- Bedard, A., Nichols, S., Barbosa, J. A., Schachar, R., Logan, G. D., & Tannock, R. (2002). The development of selective inhibitory control across the life span. *Developmental Neuropsychology*, 21(1), 93-111.
- Bedard, A. C., Ickowicz, A., Logan, G. D., Hogg-Johnson, S., Schachar, R., & Tannock, R. (2003). Selective inhibition in children with Attention-Deficit Hyperactivity Disorder off and on stimulant medication. *Journal of Abnormal Child Psychology*, 31(1), 315-327.
- Bekker, E. M., Kenemans, J. L., Hoeksma, M. R., Talsma, D., & Verbaten, M. N. (2005a). The pure electrophysiology of stopping. *International Journal of Psychophysiology*, 55(2), 191-198.
- Bekker, E. M., Kenemans, J. L., & Verbaten, M. N. (2005b). Source analysis of the N2 in a cued Go/Nogo task. *Cognitive Brain Research*, 22, 221-231.
- Bekker, E. M., Overtom, C. C. E., Kenemans, J. L., Kooij, J. J. S., de Noord, I., Buitelaar, J. K., & Verbaten, M. N. (in press). Stopping and changing in adults with ADHD. *Psychological Medicine*.
- Bekker, E. M., Overtom, C. C. E., Kooij, J. J. S., Buitelaar, J. K., Verbaten, M. N., & Kenemans, J. L. (submitted). Disentangling deficits in attention and inhibition.
- Bernstein, A. S., Schnur, D. B., Bernstein, P., Yeager, A., Wrable, J., & Smith, S. (1995a). Differing patterns of electrodermal and finger pulse responsivity in schizophrenia and depression. *Psychological Medicine*, 25(1), 51-62.
- Bernstein, P. S., Scheffers, M. K., & Coles, M. G. H. (1995b). "Where did I go wrong?" A psychophysiological analysis of error detection. *Journal of Experimental Psychology: Human Perception & Performance*, 21, 1312-1322.
- Biederman, J., Faraone, S. V., Spencer, T., Wilens, T., Norman, D., Lapey, K. A., Mick, E., Lehman, B. K., & Doyle, A. E. (1993). Patterns of psychiatric comorbidity, cognition, and psychosocial functioning in adults with attention deficit hyperactivity disorder. *American Journal of Psychiatry*, 150, 1792-1798.

- Biederman, J., & Spencer, T. (1999). Attention-deficit/hyperactivity disorder (ADHD) as a noradrenergic disorder. *Biological Psychiatry*, 46(9), 1234-1242.
- Birbaumer, N., Elbert, T., Canavan, A. G., & Rockstroh, B. (1990). Slow potentials of the cerebral cortex and behaviour. *Physiological Reviews*, 70(1), 1-41.
- Bokura, H., Yamaguchi, S., Kobayashi, S. (2001). Electrophysiological correlates for response inhibition in a Go/Nogo task. *Clinical Neurophysiology*, 112, 2224-2232.
- Brandeis, D., van Leeuwen, T. H., Rubia, K., Vitacco, D., Steger, J., Pascual-Marqui, R. D., & Steinhausen, H. C. (1998). Neuroelectric mapping reveals precursor of stop failures in children with attention deficits. *Behavioural Brain Research*, 94(1), 111-125.
- Bresnahan, S. M., Anderson, J. W., & Barry, R. J. (1999). Age-related changes in quantitative EEG in attention-deficit/hyperactivity disorder. *Biological Psychiatry*, 46(12), 1690-1697.
- Bresnahan, S. M., & Barry, R. J. (2002). Specificity of quantitative EEG analysis in adults with attention deficit hyperactivity disorder. *Psychiatry Research*, 112(2), 133-144.
- Broadbent, D. E. (1970). Stimulus set and response set: Two kinds of selective attention. In D. I. Mostofsky (Ed.), *Attention: Contemporary theory and analysis*. New York: Appleton-Century-Crofts.
- Brown, D., Fenwick, P., & Howard, R. (1989). The contingent negative variation in a Go/No Go avoidance task: Relationships with personality and subjective state. *International Journal of Psychophysiology*, 7, 35-45.
- Brown, T. E. (1995). *Brown Attention-deficit Disorders Scales*. San Antonio, Texas: Psychological Corporation.
- Bruin, K. J., & Wijers, A. A. (2002). Inhibition, response mode, and stimulus probability: a comparative event-related potential study. *Clinical Neurophysiology*, 113, 1172-1182.
- Bruin, K. J., Wijers, A. A., & van Staveren, A. S. J. (2001). Response priming in a go/nogo task: do we have to explain the go/nogo N2 effect in terms of response activation instead of inhibition. *Clinical Neurophysiology*, 112, 1660-1671.

- Brunia, C. H. M. (1993). Waiting in readiness: Gating in attention and motor preparation. *Psychophysiology*, 30, 327-339.
- Brunia, C. H. M. (1997). On the crossroads of anticipatory attention and motor preparation. In A. Kok, & A. J. W. Boelhouwer (Eds.), *Attention* (in dutch). Van Gorcum.
- Brunia, C. H. M. (2003). How is stopping realised? In M. Ullsperger, & M. Falkenstein (Eds.), *Errors, conflicts, and the brain: Current opinions on performance monitoring* (pp. 96 - 103). Leipzig: MPI cognitive neuroscience.
- Brunia, C. H. M., & van Boxtel, G. J. M. (2000). Motor preparation. In J. T. Cacioppo, L.G. Tassinary, & G. G. Berntson (Eds.), *Handbook of psychophysiology* (2<sup>nd</sup> ed., pp. 507 - 532). New York, USA: Cambridge University Press
- Bullock, D., & Grossberg, S. (1988). Neural dynamics of planned arm movements: Emergent invariants and speed-accuracy properties during trajectory formation. *Psychological Review*, 95, 49-90.
- Bush, G., Frazier, J. A., Rauch, S. L., Seidman, L. J., Whalen, P. L., Jenike, M. A., Rosen, B. R., & Biederman, J. (1999). Anterior cingulate cortex dysfunction in Attention-deficit/Hyperactivity Disorder revealed by fMRI and the counting stroop. *Biological Psychiatry*, 45, 1542-1552.
- Carrillo-de-la-Pena, M. T. (1992). ERP augmenting/reducing and sensation seeking: a critical review. *International Journal of Psychophysiology*, 12(3), 211-220.
- Carrillo-de-la-Pena, M. T., & Barratt, E. S. (1993). Impulsivity and ERP augmenting/reducing. *Personality and Individual Differences*, 15(1), 25-32.
- Carrillo-de-la-Pena, M. T., Otero, J. M., & Romero, E. (1993). Comparison among various methods of assessment of impulsiveness. *Perceptual & Motor Skills*, 77, 567-575.
- Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M. M., Noll, D., & Cohen, J. D. (1998). Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science*, 280(5364), 747-749.
- Casey, B. J., Castellanos, F. X., Giedd, J. N., & Marsh, W. L. (1997). Implication of right frontostriatal circuitry in response inhibition and attention-deficit/hyperactivity

disorder. *Journal of the American Academy of Child & Adolescent Psychiatry*, 36(3), 374-383.

- Castellanos, F. X., Giedd, J. N., Marsh, W. L., Hamburger, S. D., Vaituzis, A. C., Dickstein, D. P., Sarfatti, S. E., Vauss, Y. C., Snell, J. W., Lange, N., Kaysen, D., Krain, A. L., Ritchie, G. F., Rajapakse, J. C., & Rapoport, J. L. (1996). Equantitative brain magnetic resonance imaging in attention-deficit hyperactivity disorder. *Archives of General Psychiatry*, 53, 607-616.
- Cheung, A. M., Mitsis, E. M., & Halperin, J. M. (2004). The relationship of behavioral inhibition to executive functions in young adults. *Journal of Clinical & Experimental Neuropsychology*, 26(3), 393-404.
- Clark, J. M. (1996). Contributions of inhibitory mechanisms to unified theory in neuroscience and psychology. *Brain & Cognition*, 30(1), 127-152.
- Clarke, A. R., Barry, R. J., McCarthy, R., & Selikowitz, M. (1998). EEG analysis in Attention-Deficit/Hyperactivity Disorder: a comparative study of two subtypes. *Psychiatry Research*, 81(1), 19-29.
- Clarke, A. R., Barry, R. J., McCarthy, R., & Selikowitz, M. (2001a). EEG-defined subtypes of children with attention-deficit/hyperactivity disorder. *Clinical Neurophysiology*, 112(11), 2098-2105.
- Clarke, A. R., Barry, R. J., McCarthy, R., & Selikowitz, M. (2001b). Excess beta activity in children with attention-deficit/hyperactivity disorder: an atypical electrophysiological group. *Psychiatry Research*, 103(2-3), 205-218.
- Coles, M. G. (1989). Modern mind-brain reading: Psychophysiology, physiology, and cognition. *Psychophysiology*, 26(3), 251-269.
- Coles, M. G. H., Gratton, G., Bashore, T.R., Eriksen, C.W., Donchin, E. (1985). A psychophysiological investigation of the continuous flow model of human information processing. *Journal of Experimental Psychology: Human Perception and Performance*, 11(5), 529-553.
- Coles, M. G. H., & Rugg, M. D. (1995). Event-related brain potentials: An introduction. In M. D. Rugg, & M. G. H. Coles (Eds.), *Electrophysiology of mind : Event-related brain potentials and cognition*. New York: Oxford University Press.

- Coles, M. G. H., Scheffers, M. K., & Holroyd, C. B. (2001). Why is there an ERN/Ne on correct trials? Response representations, stimulus-related components, and the theory of error-processing? *Biological Psychology*, 56(3), 173-189.
- Conners, C. K., Epstein, J., & Johnson, D. (2001). *Conners' Adults ADHD Diagnostic Interview for DSM-IV (CAADID)*. New York: Multi-Health Systems.
- Cook, E. H., Stein, M. A., Krasowski, M. D., Cox, N. J., Olkon, D. M., Kieffer, J. E., & Leventhal, B. L. (1995). Association of attention deficit hyperactivity disorder and the dopamine transporter gene. *American Journal of Human Genetics*, 56, 993-998.
- Courchesne, E. (1978). Neurophysiological correlates of cognitive development: Changes in long latency event-related potentials from childhood to adulthood. *Electroencephalography & Clinical Neurophysiology*, 45, 468-482.
- Courchesne, E., Hillyard, S. A., & Galambos, R. (1975). Stimulus novelty, task relevance and the visual evoked potential in man. *Electroencephalography & Clinical Neurophysiology*, 39, 131-143.
- Croft, R. J., Dimoska, A., Gonzalez, C., & Clarke, A. R. (2004). P50 suppression, schizotypal beliefs, and smoking. *Psychiatry Research*, 128(1), 53-62.
- Crone, E. A., Vendel, I., & van der Molen, M. W. (2003). Decision-making in disinhibited adolescents and adults: insensitivity to future consequences or driven by immediate reward? *Personality and Individual Differences*, 35(7), 1625-1641.
- Czigler, I., Csibra, G., & Ambro, A. (1996). Aging, stimulus identification and the effect of probability: an event-related potential study. *Biological Psychology*, 43, 27-40.
- Daruna, J. H., & Barnes, P. A. (1993). A neurodevelopmental view of impulsivity. In W. G. McCown, J. L. Johnson & M. B. Shure (Eds.), *The impulsive client: Theory, research, and treatment* (pp. 23-56). Washington, DC: American Psychological Association.
- Davies, P. L., Segalowitz, S. J., Dywan, J., & Pailing, P. E. (2001). Error-negativity and positivity as they relate to other ERP indices of attentional control and stimulus processing. *Biological Psychology*, 56(3), 191-206.

- de Jong, R. (1992). Parallel processing in overlapping tasks: A model and a method. *Dissertation Abstracts International*, 52(11-B), 6112-6113, US: Univ Microfilms International.
- de Jong, R., Coles, M. G. H., & Logan, G. D. (1995). Strategies and mechanisms in nonselective and selective inhibitory motor control. *Journal of Experimental Psychology; Human Perception and Performance*, 21(3), 498-511.
- de Jong, R., Coles, M. G. H., Logan, G. D., & Gratton, G. (1990). In search of the point of no return: The control of response processes. *Journal of Experimental Psychology: Human Perception & Performance*, 16(1), 164-182.
- Diamond, S., Balvin, R. S., & Diamond, F. R. (1963). *Inhibition and choice*. New York: Harper and Row.
- Dias, R., Robbins, T. W., & Roberts, A. C. (1997). Dissociable forms of inhibitory control within prefrontal cortex with an analog of the Wisconsin Card Sort Test: Restriction to novel situations and independence from 'on-line' processing. *Journal of Neuroscience*, 17, 9285-9297.
- Dickman, S. J. (1990). Functional and dysfunctional impulsivity: Personality and cognitive correlates. *Journal of Personality and Social Psychology*, 58, 95-102.
- Dickman, S. J. (1993). Impulsivity and information processing. In W. G. McCown, J. L. Johnson & M. B. Shure (Eds.), *The impulsive client: Theory, research, and treatment* (pp. 151-183). Washington, DC: American Psychological Association.
- Dimoska, A., Johnstone, S. J., Barry, R. J., & Clarke, A. R. (2003). Inhibitory motor control in children with Attention-deficit/Hyperactivity Disorder: Event-related potentials in the stop-signal paradigm. *Biological Psychiatry*, 54(12), 1345-1354.
- Dolan, M., Anderson, I. M., & Deakin, J. F. W. (2001). Relationship between 5-HT function and impulsivity and aggression in male offenders with personality disorders. *British Journal of Psychiatry*, 178, 352-359.
- Donchin, E. (1981). Surprise . . . Surprise? *Psychophysiology*, 18(5), 493-513.
- Donchin, E., & Coles, M. G. (1988). Is the P300 component a manifestation of context updating? *Behavioral & Brain Sciences*, 11(3), 357-427.



- Donchin, E., Ritter, W., & McCallum, W. C. (1978). Cognitive psychology: The endogenous components of the ERP. In E. Callaway, P. Tueting, & S. H. Koslow (Eds.), *Brain event-related potentials in man*. New York: Academic Press.
- Donkers, F. C. L., & van Boxtel, G. J. M. (2004). The N2 in go/no-go tasks reflects conflict monitoring not response inhibition. *Brain and Cognition*, 56(2), 165-176.
- Douglas, V. I. (1972). Stop, look, and listen: The problem of sustained attention and impulse control in hyperactive and normal children. *Canadian Journal of Behavioural Science*, 4, 259-282.
- Douglas, V. I., & Parry, P.A. (1983). Effects of reward on delayed reaction time task performance of hyperactive children. *Journal of Abnormal Child Psychology*, 11, 313-326.
- Drew, E. A. (1975). Go/no-go learning after frontal lobe lesions in humans. *Cortex*, 11, 8-16.
- Duncan, J., & Owen, A. A. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neurosciences*, 23, 475-483.
- Duncan-Johnson, C. C., & Donchin, E. (1977). On quantifying surprise: The variation of event-related potentials with subjective probability. *Psychophysiology*, 14(5), 456-467.
- Durston, S., Thomas, K. M., Yang, Y., Ulug, A. M., Zimmerman, R. D., & Casey, B. J. (2002). A neural basis for the development of inhibitory control. *Developmental Science*, 5(4), F9-F16.
- Durston, S., Tottenham, N. T., Thomas, K. M., Davidson, M. C., Eigsti, I.-M., Yang, Y., Ulug, A. M., & Casey, B. J. (2003). Differential patterns of striatal activation in young children with and without ADHD. *Biological Psychiatry*, 53(10), 871-878.
- Eimer, M. (1993). Effects of attention and stimulus probability on ERPs in a Go/Nogo task. *Biological Psychology*, 35, 123-138.
- Eimer, M., & Schlaghecken, F. (1998). Effects of masked stimuli on motor activation: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception & Performance*, 24(6), 1737-1747.

- Enoki, H., Sanada, S., Yoshinaga, H., Oka, E., & Ohtahara, S. (1993). The effects of age on the N200 component of the auditory event-related potentials. *Cognitive Brain Research*, 1(3), 161-167.
- Epstein, J. N., Conners, C. K., Sitarenios, G., & Erhardt, D. (1998). Continuous performance test results of adults with Attention-deficit Hyperactivity Disorder. *The Clinical Neuropsychologist*, 12, 155-169.
- Epstein, J. N., Johnson, D. E., Varia, I. M., & Conners, C. K. (2001). Neuropsychological assessment of response inhibition in adults with ADHD. *Journal of Clinical & Experimental Neuropsychology*, 23(3), 362-371.
- Eysenck, H. J. (1993a). The nature of impulsivity. In W. G. McCown, J. L. Johnson & M. B. Shure (Eds.), *The impulsive client: Theory, research, and treatment* (pp. 57-69). Washington, DC: American Psychological Association.
- Eysenck, H. J., & Eysenck, S. B. G. (1975). *Manual of the Eysenck Personality Questionnaire*. San Diego, CA: Education and Industrial Testing Service.
- Eysenck, H. J., & Eysenck, S. B. G. (1969). *Personality structure and measurement*. San Diego: Knapp.
- Eysenck, S. B. G. (1993b). The I-sub-7: Development of a measure of impulsivity and its relationship to the superfactors of personality. In W. G. McCown, J. L. Johnson & M. B. Shure (Eds.), *The impulsive client: Theory, research, and treatment* (pp. 141-149). Washington, DC: American Psychological Association.
- Eysenck, S. B. G., & Eysenck, H. J. (1977). The place of impulsiveness in a dimensional system of personality. *British Journal of Social and Clinical Psychology*, 2, 46-55.
- Eysenck, S. B. G., & Eysenck, H. J. (1978). Impulsiveness and venturesomeness: their position in a dimensional system of personality description. *Psychological Reports*, 43, 1247-1255.
- Eysenck, S. B. G., Pearson, P. R., Easting, G., & Allsopp, J. F. (1985). Age norms for impulsiveness, venturesomeness and empathy in adults. *Personality & Individual Differences*, 6(5), 613-619.

- Fabiani, M., & Friedman, D. (1995). Changes in brain activity patterns in aging: The novelty oddball. *Psychophysiology*, 32(6), 579-594.
- Fabiani, M., Gratton, G., & Coles, M. G. H. (2000). Event-related brain potentials: Methods, theory and applications. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of psychophysiology* (2nd ed.). U.S.A.: Cambridge University Press.
- Falkenstein, M., Hohnsbein, J., & Hoorman, J. (1995a). Event-related potential correlates or errors in reaction tasks. In G. Karmos, M. Molnar, I. Csepe, & J. E. Desmedt (Eds.), *Perspectives of event-related potentials research* (Vol. EEG Suppl. 44, pp. 280-286). Amsterdam: Elsevier.
- Falkenstein, M., Hohnsbein, J., & Hoormann, J. (1994). Effects of choice complexity on different subcomponents of the late positive complex of the event-related potential. *Electroencephalography & Clinical Neurophysiology: Evoked Potentials*, 92(2), 148-160.
- Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components: II. Error processing in choice reaction tasks. *Electroencephalography & Clinical Neurophysiology*, 78(6), 447-455.
- Falkenstein, M., Hoormann, J., & Hohnsbein, J. (1999). ERP components in go/nogo tasks and their relation to inhibition. *Acta Psychologica*, 101, 267-491.
- Falkenstein, M., Hoormann, J., Christ, S., & Hohnsbein, J. (2000). ERP components on reaction errors and their functional significance: A tutorial. *Biological Psychology*, 51(2-3), 87-107.
- Falkenstein, M., Hoormann, J., & Hohnsbein, J. (2002). Inhibition-related ERP components: Variation with modality, age, and time-on-task. *Journal of Psychophysiology*, 16(3), 167-175.
- Falkenstein, M., Koshlykova, V. N., Hoormann, J., & Hohnsbein, J. (1995b). Late ERP components in visual and auditory go/nogo tasks. *Electroencephalography and Clinical Neurophysiology*, 96, 36-43.
- Fallgatter, A. J., Ehlis, A.-C., Rosler, M., Strik, W. K., Blocher, D., & Herrmann, M. J. (2005). Diminished prefrontal brain function in adults with psychopathology in

childhood related to attention deficit hyperactivity disorder. *Psychiatry Research: Neuroimaging*, 138(2), 157-169.

- Fallgatter, A. J., & Herrmann, M. J. (2001). Electrophysiological assessment of impulsive behavior in healthy subjects. *Neuropsychologia*, 39(3), 328-333.
- Fallgatter, A. J., & Strik, W. K. (1999). The NoGo-anteriorization as a neurophysiological standard-index for cognitive response control. *International Journal of Psychophysiology*, 32, 233-238.
- Fallgatter, A. J., Wiesbeck, G. A., Weijers, H. G., Boening, J., & Strik, W. K. (1998). Event-related correlates of response suppression as indicators of novelty seeking in alcoholics. *Alcohol & Alcoholism*, 33(5), 475-481.
- Faraone, S., Biederman, J., Spencer, T., Wilens, T., Seidman, L. J., Mick, E., & Doyle, A. E. (2000). Attention-deficit/Hyperactivity Disorder in Adults: An overview. *Biological Psychiatry*, 48, 9-20.
- Feifel, D., Farber, R. H., Clementz, B. A., Perry, W., & Anllo-Vento, L. (2004). Inhibitory deficits in ocular motor behavior in adults with attention-deficit/hyperactivity disorder. *Biological Psychiatry*, 56(5), 333-339.
- Filipovic, S. R., Jahanshani, M., & Rothwell, J. C. (2000). Cortical potentials related to the nogo decision. *Experimental Brain Research*, 132, 411-415.
- Friedman, D., Boltri, J., Vaughan, H., & Erlenmeyer-Kimling, L. (1985). Effects of age and sex on the endogenous brain potential components during two continuous performance tasks. *Psychophysiology*, 22(4), 440-452.
- Garavan, H., Morgan, R. E., Mactutus, C. F., Levitsky, D. A., Booze, R. M., & Strupp, B. J. (2000). Prenatal Cocaine Exposure Impairs Selective Attention: Evidence From Serial Reversal and Extradimensional Shift Tasks. *Behavioral Neuroscience*, 114(4), 725-738.
- Garavan, H., Ross, T. J., Kaufman, J., & Stein, E. A. (2003). A midline dissociation between error-processing and response-conflict monitoring. *NeuroImage*, 20(2), 1132-1139.

- Garavan, H., Ross, T. J., Murphy, K., Roche, R. A. P., & Stein, E. A. (2002). Dissociable Executive Functions in the Dynamic Control of Behavior: Inhibition, Error Detection, and Correction. *NeuroImage*, 17(4), 1820-1829.
- Garavan, H., Ross, T. J., & Stein, E. A. (1999). Right hemispheric dominance of inhibitory control: An event-related functional MRI study. *Proceedings of the National Academy of Science*, 96(14), 8301-8306.
- Gasser, T., Verleger, R., Bacher, P., & Sroka, L. (1988). Development of the EEG of school-aged children and adolescents. I. Analysis of band power. *Electroencephalography & Clinical Neurophysiology*, 69, 91-99.
- Gehring, W. J. (1992). *The error-related negativity: Evidence for a neural mechanism for error-related processing*. Unpublished doctoral dissertation, University of UIllinois, Urbana-Champaign, US.
- Gehring, W. J., Coles, M. G. H., Meyer, D. E., & Donchin, E. (1995). A brain potential manifestation of error-related processing. *Perspectives of Event-Related Potentials Research: EEG Supplement 44*, 44, 261-272.
- Gehring, W. J., & Fencsik, D. E. (1999, April 11-13, 1999). *Slamming on the brakes: An electrophysiological study of error response inhibition*. Paper presented at the Annual Meeting of the Cognitive Neuroscience Society, Washington, USA.
- Gehring, W. J., Goss, B., Coles, M. G., Meyer, D. E., & Donchin, E. (1993). A neural system for error detection and compensation. *Psychological Science*, 4(6), 385-390.
- Gerbing, D. W., Ahadi, S. A., & Patton, J. H. (1987). Towards a conceptualisation of impulsivity: Components across the behavioural and self-report domains. *Multivariate Behavioural Research*, 22, 357-379.
- Gerstle, J. E., Mathias, C. W., & Stanford, M. S. (1998). Auditory P300 and self-reported impulsive aggression. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, 22(4), 575-583.
- Goldberg, D. P., & Hillier, V. F. (1979). A scaled version of the General health Questionnaire. *Psychological Medicine*, 9, 139-145.

- Goldberg, G. (1985). Supplementary motor area structure and function: Review and hypotheses. *Behavioral & Brain Sciences*, 8(4), 567-616.
- Gorlyn, M., Keilp, J. G., Tryon, W. W., & Mann, J. J. (2005). Performance test correlates of component factors of impulsiveness. *Personality and Individual Differences*, 38(7), 1549-1559.
- Gratton, G., Coles, M. G. H., Sirevaag, E., Eriksen, C.W., & Donchin, E. (1988). Pre- and poststimulus activation of response channels: A psychophysiological analysis. *Journal of Experimental Psychology: Human Perception and Performance*, 14, 331-344.
- Gray, J. A. (1987). The neuropsychology of emotion and personality. In S. M. Stahl, S. D. Iverson & E. C. Goodman (Eds.), *Cognitive neurochemistry* (Vol. 171-190). Oxford, England: Oxford University Press.
- Gray, J. A. (1991). Neural systems, emotion and personality. In J. Madden (Ed.), *Neurobiology of learning, emotion and affect* (pp. 273-306). New York: Raven Press.
- Guthrie, D. (1990). Intergroup and intrasubject principal components analysis of event-related potentials. *Psychophysiology*, 27(1), 111-119.
- Hackley, S. A., & Valle-Inclan, F. (1999). Accessory stimulus effects on response selection: does arousal speed decision making? *Journal of Cognitive Neuroscience*, 11(3), 321-330.
- Hajcak, G., Vidal, F., & Simons, R. F. (2003). Difficulties With Easy Tasks: ERN/Ne and Stimulus Component Overlap. In M. Ullsperger, & M. Falkenstein (Eds.), *Errors, conflicts, and the brain: Current opinions on performance monitoring* (pp. 204 - 211). Leipzig: MPI cognitive neuroscience.
- Hanes, D. P. and R. H. S. Carpenter (1999). Countermanding saccades in humans. *Vision Research*, 39(16), 2777-2791.
- Hansen, J. C., & Hillyard, S. A. (1988). Temporal dynamics of human auditory selective attention. *Psychophysiology*, 25(3), 316-329.

- Harmon-Jones, E., Barratt, E. S., & Wigg, C. (1997). Impulsiveness, aggression, reading, and the P300 of the event-related potential. *Personality and Individual Differences*, 22(4), 439-445.
- Harnishfeger, K. K., & Bjorklund, D. F. (1994). A developmental perspective on individual differences in inhibition. *Learning & Individual Differences*, 6(3), 331-355.
- Hart, E. L., Lahey, B. B., & Kazdin, A. E., Loeber, R., Applegate, B., & Frick, P. J. (1995). Developmental changes in attention-deficit hyperactivity disorder in boys: A four year longitudinal study. *Journal of Abnormal Child Psychology*, 23, 729-750.
- Haslam, N. (2003). Categorical versus dimensional models of mental disorder: The taxometric evidence. *Australian and New Zealand Journal of Psychiatry*, 37, 696-704.
- Hegerl, U., & Juckel, G. (1993). Intensity dependence of auditory evoked potentials as an indicator of central serotonergic neurotransmission: A new hypothesis. *Biological psychiatry*, 33, 173-187.
- Hegerl, U., Karnauchow, I., Herrmann, W. M., & Mueller-Oerlinghausen, B. (1992). Intensity dependence of auditory evoked N1/P2 component and personality. *Neuropsychobiology*, 26(3), 166-172.
- Hervey, A. S., Epstein, J. N., & Curry, J. F. (2004). Neuropsychology of adults with Attention-Deficit/Hyperactivity Disorder: A meta-analytic review. *Neuropsychology*, 18(3), 485-503.
- Hill, J., & Shoener, E. (1996). Age-dependent decline of attention deficit hyperactivity disorder. *American Journal of Psychiatry*, 153, 1143-1146.
- Hillyard, S. A. (1981). Selective auditory attention and early event-related potentials: A rejoinder. *Canadian Journal of Psychology*, 35(2), 159-174.
- Hillyard, S. A., Courchesne, E., Krauz, H. I., & Picton, T. W. (1976). Scalp topography of the P3 wave in different auditory decision tasks. In W. C. McCallum & J. R. Knott (Eds.), *The responsive brain* (pp. 81-87). Bristol: John Wright.
- Hillyard, S. A., & Hansen, J. C. (1991). Attention: Electrophysiological approaches. In J. R. Jennings & M. G. H. Coles (Eds.), *Handbook of cognitive psychophysiology*:

*Central and autonomic nervous system approaches* (pp. 227-243). Chichester, England: John Wiley & Sons.

Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. (1973). Electrical signs of selective attention in the human brain. *Science*, 182, 177-180.

Hillyard, S. A., Vogel, E. K., & Luck, S. J. (1998). Sensory gain control (amplification) as a mechanism of selective attention: electrophysiological and neuroimaging evidence. *Philosophical Transactions of the Royal Society: Biological Sciences*, 353, 1257-1270.

Hinshaw, S. (2003). Impulsivity, emotion regulation, and developmental psychopathology: Specificity versus generality of linkages. *Annals of the New York Academy of Sciences*, 1008, 149-159.

Hohnsbein, J., Falkenstein, M., Hoorman, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components. I. Simple and choice reaction tasks. *Electroencephalography and Clinical Neurophysiology*, 78, 438-446.

Holcomb, P. J., Ackerman, P.T., & Dykman, R.A. (1986). Auditory event-related potentials in attention and reading disabled boys. *International Journal of Psychophysiology*, 3, 263-273.

Horn, N. R., Dolan, M., Elliott, R., Deakin, J. F. W., & Woodruff, P. W. R. (2003). Response inhibition and impulsivity: An fMRI study. *Neuropsychologia*, 41(14), 1959-1966.

Houston, R. J., & Stanford, M. S. (2001). Mid-latency evoked potentials in self-reported impulsive aggression. *International Journal of Psychophysiology*, 40(1), 1-15.

Houston, R. J., & Stanford, M. S. (2005). Electrophysiological substrates of impulsiveness: potential effects on aggressive behaviour. *Progress in Neuro-Psychopharmacology & Biological Psychiatry*, 29(2), 305-313.

Howard, R., Fenton, G. W., & Fenwick, P. B. (1980). Slow cerebral potentials in a 'go-no go' avoidance situation: a study on special hospital patients. In C. Barber (Ed.), *Evoked Potentials*. Baltimore, MD: University Park Press.



- Hsieh, S., & Yen-Ting, Y. (2003). Switching between simple response-sets: inferences from the lateralized readiness potential. *Cognitive Brain Research*, 17, 229-237.
- Huang, Z., Stanford, M. S., & Barratt, E. S. (1994). Blink rate related to impulsiveness and task demands during performance of event-related potential tasks. *Personality and Individual Differences*, 16(4), 645-648.
- Hunt, R. D., Mandl, L., Lau, S., & Hughes, M. (1991). Neurobiological theories of ADHD and Ritalin. In L. L. Greenhill & B. B. Osman (Eds.), *Ritalin: Theory and patient management* (pp. 267-287). New York: Mary Ann Liebert, Inc.
- Iwaki, N., Miyatani, M., & Toshima, T. (2003). A psychophysiological study on the function of the response-stop in the Eriksen task. *Japanese Psychological Research*, 45(2), 100-108.
- Jasper, H. H. (1958). The 10-20 electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*, 10, 371-375.
- Jennings, J. R., van der Molen, M.W., Brock, K., & Somsen, R.J.M. (1992). On the synchrony of stopping motor responses and delaying heartbeats. *Journal of Experimental Psychology: Human Perception and Performance*, 18(2), 422-436.
- Jodo, E., & Kayama, Y. (1992). Relation of a negative ERP component to response inhibition in a go/no go task. *Electroencephalography Clinical Neurophysiology*, 82, -47.
- Johnson, D. E., Epstein, J. N., Waid, L. R., Latham, P. K., Voronin, K. E., & Anton, R. F. (2001). Neuropsychological performance deficits in adults with attention deficit/hyperactivity disorder. *Archives of Clinical Neuropsychology*, 16(6), 587-604.
- Johnson, R. (1993). On the neural generators of the P300 component of the event-related potential. *Psychophysiology*, 30, 90-97.
- Johnson, R., & Donchin, E. (1978). On how P300 amplitude varies with the utility of the eliciting stimuli. *Electroencephalography & Clinical Neurophysiology*, 44(4), 424-437.

- Johnstone, S. J., & Barry, R. J. (1996). Auditory event-related potentials to a two-tone discrimination paradigm in attention deficit hyperactivity disorder. *Psychiatry Research*, 64(3), 179-192.
- Johnstone, S. J., & Barry, R. J. (1999). An investigation of the event-related slow-wave potential (0.01-2 Hz) in normal children. *International Journal of Psychophysiology*, 32(1), 15-34.
- Johnstone, S. J., Barry, R. J., Anderson, J. W., & Coyle, S. F. (1996). Age-related changes in child and adolescent event-related potential component morphology, amplitude and latency to standard and target stimuli in an oddball task. *International Journal of Psychophysiology*, 24, 223-238.
- Johnstone, S. J., Barry, R. J., & Dimoska, A. (2003). Event-related slow-wave activity in two subtypes of attention-deficit/hyperactivity disorder. *Clinical Neurophysiology: Official Journal Of The International Federation Of Clinical Neurophysiology*, 114(3), 504-514.
- Johnstone, S. J., Barry, R.J., & Anderson, J.W. (2001). Topographic distribution and developmental timecourse of auditory event-related potentials in two subtypes of attention-deficit hyperactivity disorder. *International Journal of Psychophysiology*, 42, 73-94.
- Jouvent, R., & Pierson, A. (1998). Cognitive psychophysiology of impulsivity and loss of control. *European Psychiatry*, 13(Supplement 4), 181s.
- Karayanidis, F., Coltheart, M., Michie, P. T., & Murphy, K. (2003). Electrophysiological correlates of anticipatory and poststimulus components of task switching. *Psychophysiology*, 40(3), 329-348.
- Karayanidis, F., Robaey, P., Bourassa, M., de Koning, D., Geoffroy, G., & Pelletier, G. (2000). ERP differences in visual attention processing between attention-deficit hyperactivity disorder and control boys in the absence of performance differences. *Psychophysiology*, 37(3), 319-333.
- Karlin, L., & Martz, M. J. (1973). Response Probability and Sensory-Evoked Potentials. In S. Kornblum (Ed.), *Attention and performance* (4<sup>th</sup> ed., pp. 175-184). New York: Academic Press.

- Kaufer, D. I., & Lewis, D. A. (1999). Frontal lobe anatomy and cortical connectivity. In B. L. Miller & J. L. Cummings (Eds.), *The human frontal lobes: Functions and disorders* (pp. 27-44). New York: The Guilford Press.
- Kelly, A. M. C., Hester, R., Murphy, K., Javitt, D. C., Foxe, J. J., & Garavan, H. (2004). Prefrontal-subcortical dissociations underlying inhibitory control revealed by event-related fMRI. *European Journal of Neuroscience*, 19, 3105-3112.
- Kiefer, M., Marzinzik, F., Weisbrod, M., Scherg, M., & Spitzer, M. (1998). The time course of brain activations during response inhibition: Evidence from event-related potentials in a go/no go task. *Neuroreport: an International Journal for the Rapid Communication of Research in Neuroscience*, 9(4), 765-770.
- Kiehl, K. A., Smith, A. M., Hare, R. D., & Liddle, P. F. (2000). An event-related potential investigation of response inhibition in schizophrenia and psychopathy. *Biological Psychiatry*, 48(3), 210-221.
- Kindlon, D., Mexxacappa, E., & Earls, F. (1995). Psychometric properties of impulsivity measures: Temporal stability, validity and factor structure. *Journal of Child Psychological Psychiatry*, 36, 645-661.
- Kok, A. (1986). Effects of degradation of visual stimuli on components of the event-related potential (ERP) in Go/Nogo reaction tasks. *Biological Psychology*, 23, 21-28.
- Kok, A. (1997). Event-related potential (ERP) reflections of mental resources: a review and synthesis. *Biological Psychology*, 45, 19-56.
- Kok, A. (1999). Varieties of inhibition: Manifestations in cognition, event-related potentials and aging. *Acta Psychologica*, 101(2-3), 129-158.
- Kok, A., Ramautar, J., de Ruiter, M., Band, G. P. H., & Ridderinkhof, K. R. (2004). ERP components associated with successful and unsuccessful inhibition in a stop-signal task. *Psychophysiology*, 41(1), 9-20.
- Konishi, S., Nakajima, K., Uchida, I., Kikyo, H., Kameyama, M., & Miyashita, Y. (1999). Common inhibitory mechanisms in human inferior prefrontal cortex revealed by event-related functional MRI. *Brain*, 122, 981-991.

- Kopp, B., Mattler, U., Goertz, R., & Rist, F. (1996). N2, P3 and the lateralised readiness potential in a nogo task involving selective response priming. *Electroencephalography and Clinical Neurophysiology*, 99, 19-27.
- Kopp, B., Rist, F., & Mattler, U. (1996). N200 in the flanker task as a neurobehavioral tool for investigating executive control. *Psychophysiology*, 33, 282-294.
- Kornhuber, H. H., & Deecke, L. (1965). Hirnpotentialänderungen bei Willkürbewegungen und passiven Bewegungen des Menschen: Bereitschaftspotential und reafferente Potentiale. *Pfugers Archiv für die gesamte Physiologie*, 248, 1-17.
- Kramer, A. F., Humphrey, D.G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging*, 9(4), 491-513.
- Krijns, P. W., Gaillard, A. W. K., Van Heck, G. L., & Brunia, C. H. M. (1994). Personality effects on brain potentials in an S1-S2 paradigm. *Personality and Individual Differences*, 16(4), 561-570.
- Kruesi, M. J., Rapuport, J. L., Hamburger, S., Hibbs, E., Potter, W. Z., Lenane, M., & Brown, G. L. (1990). Cerebrospinal fluid monoamine metabolites, aggression, and impulsivity in disruptive behaviour of children and adolescents. *Archives of General Psychiatry*, 47, 419-426.
- Kubose, S. (2000). ADHD in adults: Are the current diagnostic criteria adequate? *NeuroPsychiatry Reviews*, 1(1).
- Kuntsi, J., Oosterlaan, J., & Stevenson, J. (2001). Psychological mechanisms in hyperactivity: I Response inhibition deficit, working memory impairment, delay aversion, or something else? *Journal of Child Psychology & Psychiatry & Allied Disciplines*, 42(2), 199-210.
- Kutas, M., & Donchin, E. (1980). Preparation to respond as manifested by movement-related brain potentials. *Brain Research*, 202, 95-115.
- Ladefoged, P., Silverstein, R., & Papcun, G. (1973). Interruptibility of speech. *Journal of the Acoustical Society of America*, 54, 1105-1108.

- Lappin, J. S., & Ericksen, C. W. (1966). Use of a delayed signal to stop a visual reaction-time response. *Journal of Experimental Psychology*, 72, 805-811.
- Lazzaro, I., Anderson, J., Gordon, E., Clarke, S., Leong, J., & Meares, R. (1997). Single trial variability within the P300 (250-500 ms) processing window in adolescents with attention deficit hyperactivity disorder. *Psychiatry Research*, 73(1-2), 91-101.
- Leuthold, H. (2003). Programming of expected and unexpected movements: effects on the onset of the lateralised readiness potential. *Acta Psychologica*, 114, 83-100.
- Lijffijt, M., Bekker, E. M., Quik, E. H., Bakker, J., Kenemans, J. L., & Verbaten, M. N. (2004). Differences between low and high trait impulsivity are not associated with differences in inhibitory motor control. *Journal Of Attention Disorders*, 8(1), 25-32.
- Lijffijt, M., Kenemans, J. L., Ter Wal, A., Quick, E. H., Kemner, C., Westernberg, H., Verbaten M.N., & van Engeland, H. (submitted). Dose-related effect of methylphenidate on stopping and changing in children with attention-deficit/hyperactivity disorder.
- Lijffijt, M., Kenemans, J. L., Verbaten M.N., & van Engeland, H. (2005). A meta-analytic review of stopping performance in Attention-deficit/Hyperactivity Disorder: Deficient inhibitory motor control? *Journal of Abnormal Psychology*, 114(2), 216-222.
- Lisberger, S. G., Fuchs, A. F., King, W. M., & Evinger, L. C. (1975). Effect of mean reaction time on saccadic responses to two-step stimuli with horizontal and vertical components. *Vision Research*, 15, 1021-1025.
- Logan, G. D. (1981). Attention, automaticity, and the ability to stop a speeded choice response. In J. Long, & A. D. Baddeley (Eds.), *Attention and performance IX* (pp. 205-222). Hillsdale, N.J.: Erlbaum.
- Logan, G. D. (1982). On the ability to inhibit complex movements: A stop-signal study of typewriting. *Journal of Experimental Psychology: Human Perception and Performance*, 8(6), 778-792.
- Logan, G. D. (1983). On the ability to inhibit simple thoughts and actions: I. Stop-signal studies of decision and memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 9(4), 585-606.

- Logan, G. D. (1994). On the ability to inhibit thought and action: A user's guide to the stop signal paradigm. In D. Dagenbach, & Carr, T.H. (Ed.), *Inhibitory processes in attention, memory and language* (pp. 189-239). San Diego, CA: Academic Press.
- Logan, G. D. (2002). Parallel and serial processing. In H. E. W. Pashler, John (Ed) (Ed.), *Stevens' handbook of experimental psychology (3rd ed.* NY, US: John Wiley & Sons, Inc.
- Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*, 91, 295-327.
- Logan, G. D., & Barber, C. Y. (1985). On the ability to inhibit complex thoughts: A stop-signal study of arithmetic. *Bulletin of the Psychonomic Society*, 23(5).
- Logan, G. D., & Burkell, J. (1986). Dependence and independence in responding to double stimulation: a comparison of stop, change, and dual-task paradigms. *Journal of Experimental Psychology: Human Perception and Performance*, 12(4), 549-563.
- Logan, G. D., Cowan, W. B., & Davis, K. A. (1984). On the ability to inhibit simple and choice reaction time responses: A model and a method. *Journal of Experimental Psychology: Human Perception & Performance*, 10(2), 276-291.
- Logan, G. D., & Irwin, D. E. (2000). Don't look! Don't touch! Inhibitory control of eye and hand movements. *Psychonomic Bulletin & Review*, 7(1), 107-112.
- Logan, G. D., Kantowiatz, B. H., & Riegler, G. L. (1986). *On the ability to inhibit selectively: Mechanisms of response interdiction in choice reaction time.* Unpublished manuscript.
- Logan, G. D., Schachar, R. J., & Tannock, R. (1997). Impulsivity and inhibitory control. *Psychological Science*, 8(1), 60-64.
- Love, J. M. (2003). *A prefrontal profile of impulsivity: A neuropsychological approach.* Unpublished doctoral dissertation, University of New Orleans, US.
- Maher, B. S., Marazita, M. L., Ferrel, R. E., & Vanyukov, M. M. (2002). Dopamine system genes and attention deficit hyperactivity disorder: a meta analysis. *Psychiatric Genetics*, 12, 207-215.

- Mannuzza, S., Gittelman-Klien, R., Bonagura, N., Malloy, P., Giampino, T. L., & Addalli, K. A. (1991). Hyperactive boys almost grown up: V. Replication of psychiatric status. *Archives of General Psychiatry*, 48, 77-83.
- Marsh, D. M., Dougherty, D. M., Mathias, C. W., Moeller, F. G., & Hicks, L. R. (2002). Comparisons of women with high and low trait impulsivity using behavioral models of response-disinhibition and reward-choice. *Personality & Individual Differences*, 33(8), 1291-1310.
- Mathalon, D. H., Whitfield, S. L., & Ford, J. M. (2003). Anatomy of an error: ERP and fMRI. *Biological Psychology*, 64(1-2), 119-141.
- Mathias, C. W., & Stanford, M. S. (1999). P300 under standard and surprise conditions in self-reported impulsive aggression. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, 23(6), 1037-1051.
- Mathias, C. W., & Stanford, M. S. (2003). Impulsiveness and arousal: heart rate under conditions of rest and challenge in healthy males. *Personality and Individual Differences*, 35(2), 355-371.
- Mattes, S., & Ulrich, R. (1997). Response force is sensitive to the temporal uncertainty of response stimuli. *Perception & Psychophysics*, 59, 1089-1097.
- Matthys, W. v. G., S.H.M. (1998). The dominance of behavioural activation over behavioural inhibition in conduct disordered boys with or without attention deficit hyperactivity disorder. *Journal of Child Psychology and Psychiatry*, 39(5), 643-651.
- McCarthy, G., & Wood, C. C. (1985). Scalp distributions of event-related potentials: An ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology*, 62, 203-208.
- McGarry, T., Chua, R., & Franks, I. M. (2003). Stopping and restarting an unfolding action at various times. *Quarterly Journal of Experimental Psychology A*, 4, 601-620.
- McGarry, T., & Franks, I. M. (2000). Inhibitory motor control in stop paradigm: comment on Band and van Boxtel (1999). *Acta Psychologica*, 105, 83-88.
- McGarry, T., & Franks, I. M. (2003). On the nature of stopping an earlier intended voluntary action. *Motor Control*, 7(2), 155-198.

- Mehta, Y. B. (2002). *Neural correlates of inhibitory motor control: Evidence from magnetoencephalography*. Unpublished masters thesis, University of Toronto, Toronto.
- Melara, R. D., Rao, A., & Tong, Y. (2002). The Duality of Selection: Excitatory and Inhibitory Processes in Auditory Selective Attention. *Journal of Experimental Psychology: Human Perception and Performance*, 28(2), 279-306.
- Menon, V., Adelman, N. E., White, C. D., Glover, G. H., & Reiss, A. L. (2001). Error-related brain activation during a Go/Nogo response inhibition task. *Human Brain Mapping*, 12, 131-143.
- Mick, E., Biederman, J., Prince, J., Fischer, M. J., & Faraone, S. V. (2002). Impact of low birth weight on attention-deficit/hyperactivity disorder. *Journal of Developmental & Behavioral Pediatrics*, 23, 16-22.
- Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, 24, 167-202.
- Miller, J., Hackley, S. A., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology*, 35, 99-115.
- Miller, J., Riehle, A., & Requin, J. (1992). Effects of Preliminary Perceptual Output on Neuronal Activity of the Primary Motor Cortex. *Journal of Experimental Psychology: Human Perception & Performance*, 18(4), 1139-1157.
- Miller, J. O., & Low, K. (2001). Motor processes in simple, Go/No-Go, and choice reaction time tasks: A psychophysiological analysis. *Journal of Experimental Psychology: Human Perception and Performance*, 27(2), 266-289.
- Moeller, F., Barratt, E. S., Dougherty, D. M., Schmitz, J. M., & Swann, A. C. (2001). Psychiatric aspects of impulsivity. *American Journal of Psychiatry*, 158(11), 1783-1793.
- Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science*, 229, 782-784.



- Mordkoff, J. T., & Gianaros, P. J. (2000). Detecting the onset of the lateralized readiness potential: A comparison of available methods and procedures. *Psychophysiology*, 37, 347-360.
- Mostofsky, S. H., Schafer, J. G. B., Abrans, M. T., Goldberg, M. C., Flower, A. A., Boyce, A., Courtney, S. M., Calhoun, V. D., Kraut, M. A., Denckla, M. B., & Pekar, J. J. (2003). fMRI evidence that the neural basis of response inhibition is task-dependent. *Cognitive Brain Research*, 17, 419-430.
- Murphy, K. R., Barkley, R. A., & Bush, T. (2001). Executive functioning and olfactory identification in young adults with Attention Deficit-Hyperactivity Disorder. *Neuropsychology*, 15(2), 211-220.
- Murphy, P. (2002). Inhibitory control in adults with Attention-Deficit/Hyperactivity Disorder. *Journal of Attention Disorders*, 6(1), 1-4.
- Näätänen, R. (1982). Processing negativity: An evoked-potential reflection of selective attention. *Psychological Bulletin*, 92(3), 605-640.
- Näätänen, R. (1992). *Attention and brain function*. Hillsdale, N.J.: Lawrence Erlbaum Associates.
- Näätänen, R., & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: A review and an analysis of the component structure. *Psychophysiology*, 24(4), 375-425.
- Näätänen, R., & Alho, K. (1995). Mismatch negativity - A unique measure of sensory processing in audition. *International Journal of Neuroscience*, 80, 317-337.
- Näätänen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). The N1 effect of selective attention reinterpreted. *Acta Psychologica*, 42(3), 13-29.
- Näätänen, R., & Michie, P. T. (1979). Early selective-attention effects on the evoked potential: A critical review and reinterpretation. *Biological Psychology*, 8, 81-136.
- Näätänen, R., & Picton, T. W. (1986). N2 and automatic versus controlled processes. *Cerebral Psychophysiology: Studies in Event-Related Potentials, EEG Supplement*, 38, 169-186.

- Naito, E., & Matsumura, M. (1996). Movement-related potentials associated with motor inhibition under different preparatory states during performance of two visual stop signal paradigms in humans. *Neuropsychologia*, 34(6), 565-573.
- Nieuwenhuis, S., Ridderinkhof, K. R., Blom, J., Band, G. P. H., & Kok, A. (2001). Error-related brain potentials are differentially related to awareness of response errors: Evidence from an antisaccade task. *Psychophysiology*, 38(5), 752-760.
- Nieuwenhuis, S., Yeung, N., & Cohen, J. D. (2004). Stimulus modality, perceptual overlap, and the go/no-go N2. *Psychophysiology*, 41(1), 157-160.
- Nieuwenhuis, S., Yeung, N., van den Wildenberg, W., & Ridderinkhof, K. R. (2003). Electrophysiological correlates of anterior cingulate function in a go/no-go task: Effects of response conflict and trial type frequency. *Cognitive, Affective, & Behavioural Neuroscience*, 3(1), 17-26.
- Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, 126, 220-246.
- Nigg, J. T. (2001). Is ADHD a disinhibitory disorder? *Psychological Bulletin*, 127(5), 571-598.
- Nigg, J. T. (2002). Inhibitory processes in adults with persistent childhood onset ADHD. *Journal of Consulting & Clinical Psychology*, 70(1), 153-157.
- NSW Health Pharmaceutical Services Branch. (2003). *Criteria for the diagnosis and management of Attention Deficit Hyperactivity Disorder in adults* (Publication No. TG 190/3). NSW, Australia.
- Oades, R. D. (1998). Frontal, temporal and lateralized brain function in children with attention-deficit hyperactivity disorder: A psychophysiological and neuropsychological viewpoint on development. *Behavioural Brain Research*, 94, 83-95.
- Oades, R. D. (2002). Dopamine (DA) may be 'hyper' with respect to noradrenaline (NA) metabolism, but 'hypo' with respect to serotonin (5-HT) metabolism in ADHD children. *Behavioural Brain Research*, 130, 97-102.

- Oades, R. D., Dittmann-Balcar, A., & Zerbin, D. (1997). Development and topography of auditory event-related potentials (ERPs): Mismatch and processing negativity in individuals 8-22 years of age. *Psychophysiology*, 34, 677-693.
- Oades, R. D., Slusarek, M., Velling, S., & Bondy, B. (2002). Serotonin platelet-transporter measures in childhood attention-deficit/hyperactivity disorder (ADHD): clinical versus experimental measures of impulsivity. *World Journal of Biological Psychiatry*, 3, 96-100.
- Olincy, A., Ross, R. G., Harris, J. G., Young, D. A., McAndrews, M. A., Cawthra, E., McRae, K. A., Sullivan, B., Adler, L. E., & Freedman, R. (2000). The P50 auditory event-evoked potential in adult attention-deficit disorder: Comparison with schizophrenia. *Biological Psychiatry*, 47(11), 969-977.
- Ollman, R. T. (1973). Simple reactions with random countermanding of the "go" signal. In S. Kornblum (Ed.), *Attention and performance* (4<sup>th</sup> ed., pp. 571-581). New York: Academic Press.
- Oosterlaan, J., & Sergeant, J.A. (1998). Response inhibition and response re-engagement in attention-deficit/hyperactivity, anxious and normal children. *Behavioural Brain research*, 94, 33-43.
- Oosterlaan, J., Logan, G. D., & Sergeant, J. A. (1998). Response inhibition in AD/HD, CD, comorbid AD/HD + CD, anxious, and control children: a meta-analysis of studies with the stop task. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, 39(3), 411-425.
- Oosterlaan, J., & Sergeant, J. A. (1996). Inhibition in ADHD, aggressive, and anxious children: a biologically based model of child psychopathology. *Journal of Abnormal Child Psychology*, 24(1), 19-36.
- Osman, A., Kornblum, S., & Meyer, D.E. (1986). The point of no return in choice reaction time: Controlled and ballistic stages of response preparation. *Journal of Experimental Psychology: Human Perception and Performance*, 12(3), 243-258.
- Osman, A., Moorer, C. M., & Ulrich, R. (2003). Temporal organization of covert motor processes during response selection and preparation. *Biological Psychology*, 64, 47-75.

- Osman, A. M., & Moorer, C. M. (1993). The locus of dual-task interference: Psychological refractory effects on movement-related potentials. *Journal of Experimental Psychology: Human Perception & Performance*, 19, 1292-1312.
- Ossmann, J. M., & Mulligan, N. W. (2003). Inhibition and attention deficit hyperactivity disorder in adults. *American Journal of Psychology*, 116(1), 35-50.
- Overtom, C. C., Kenemans, J. L., Verbaten, M. N., Kemner, C., van der Molen, M. W., van Engeland, H., Buitelaar, J. K., & Koelega, H. S. (2002). Inhibition in children with attention-deficit/hyperactivity disorder: a psychophysiological study of the stop task. *Biological Psychiatry*, 51(8), 668-676.
- Overtom, C. C. E., Bekker, E. M., Kenemans, J. L., Verbaten, M. N., van der Molen, M. W., Kooij, J. J. S., & Buitelaar, J. K. (submitted). Effects of 2 doses MPH and 20 mg paroxetine on attention and inhibition in adults with ADHD.
- Overtom, C. C. E., Verbaten, M. N., Kemner, C., Kenemans, J. L., Engeland, H. v., Buitelaar, J. K., van der Molen, M. W., van der Gugten, J., Westenberg, H., & Maes et, a. (2003). Effects of methylphenidate, desipramine, and L-dopa on attention and inhibition in children with Attention Deficit Hyperactivity Disorder. *Behavioural Brain Research*, 145(1-2), 7-15.
- Oxford. (1933). *The oxford english dictionary* (2nd ed., Vol. H-K). London: Oxford University Press.
- Pailing, P. E., & Segalowitz, S. J. (2004). The error-related negativity as a state and trait measure: Motivation, personality, and ERPs in response to errors. *Psychophysiology*, 41, 84-95.
- Pailing, P. E., Segalowitz, S. J., Dywan, J., & Davies, P. L. (2002). Error negativity and response control. *Psychophysiology*, 39(2), 198-206.
- Parker, J. D. A., & Bagby, R. M. (1997). Impulsivity in adults: A critical review of measurements approaches. In C. D. Webster & M. A. Jackson (Eds.), *Impulsivity: Theory, assessment, and treatment* (pp. 142-157). New York: The Guilford Press.
- Patton, J. H., Stanford, M. S., & Barratt, E. S. (1995). Factor structure of the Barratt Impulsiveness Scale. *Journal of Clinical Psychology*, 51, 768-774.

- Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry*, 37, 51-87.
- Pfefferbaum, A., & Ford, J. M. (1988). ERPs to stimuli requiring response production and inhibition: Effects of age, probability and visual noise. *Electroencephalography & Clinical Neurophysiology: Evoked Potentials*, 71(1), 55-63.
- Pfefferbaum, A., Ford, J. M., Weller, B. J., & Kopell, B. S. (1985). ERPs to response production and inhibition. *Electroencephalography and Clinical Neurophysiology*, 60, 423-434.
- Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R. J., Miller, G. A., Ritter, W., Ruchkin, D. S., Rugg, M. D., & Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: Recording standards and publication criteria. *Psychophysiology*, 37, 127-152.
- Pliszka, S. R., Liotti, M., & Woldorff, M. G. (2000). Inhibitory control in children with attention-deficit/hyperactivity disorder: event-related potentials identify the processing component and timing of an impaired right-frontal response-inhibition mechanism. *Biological Psychiatry*, 48(3), 238-246.
- Pliszka, S. R., McCracken, J. T., & Maas, J. W. (1996). Catecholamines in Attention-deficit Hyperactivity Disorder: Current Perspectives. *Journal of the American Academy of Child & Adolescent Psychiatry*, 35(3), 264-271.
- Podlesny, J. A., Dustman, R. E., & Shearer, D. E. (1984). Aging and respond-withhold tasks: Effects on sustained potentials, P3 responses and late activity. *Electroencephalography & Clinical Neurophysiology*, 58, 130-139.
- Price, T. S., Simonoff, E. M. D., Waldman, I., Asherson, P., & Plomin, R. (2001). Hyperactivity in preschool children is highly heritable. *Journal of the American Academy of Child & Adolescent Psychiatry*, 40(12), 1362-1364.
- Pritchard, W. S., Shappell, S. A., & Brandt, M. E. (1991). Psychophysiology N200/N400: A review and classification scheme. In J. R. Jennings, P. K. Ackles, & M. G. H. Coles (Eds.), *Advances in psychophysiology* (Vol. 4, pp. 43-106). London: Jessica Kinglsey.
- Pritchard, W. S., Brandt, M. E., & Barratt, E. S. (1986). Analyzing event-related potentials: The utility of high and low pass filtering in improving the relationship between

various amplitude measures and principal components analysis factor scores.  
*Psychophysiology*, 23(2), Mar.

- Quay, H. C. (1988). The behavioural reward and inhibition system in childhood disorders. In L. M. Bloomingdale (Ed.), *Attention Deficit Disorder* (Vol. 3, pp. 176-186). New York: Pergamon.
- Quay, H. C. (1997). Inhibition and attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology*, 25(1), 7-13.
- Quist, J. F., & Kennedy, J. L. (2001). Genetics of childhood disorders: XXIII. ADHD, Part 7: The serotonin system. *Journal of the American Academy of Child & Adolescent Psychiatry*, 40(2), 253-257.
- Ramautar, J. R., Kok, A., & Ridderinkhof, K. R. (2004). Effects of stop-signal probability in the stop-signal paradigm: The N2/P3 complex further validated. *Brain and Cognition*, 56(2), 234-252.
- Raven, J. (2000). The Raven's progressive matrices: Changes and stability over culture and time. *Cognitive psychology*, 41, 1-48.
- Ridderinkhof, K. R., Band, G. P. H., & Logan, G. D. (1999). A study of adaptive behavior: Effects of age and irrelevant information on the ability to inhibit one's actions. *Acta Psychologica*, 101(2-3), 315-337.
- Rieger, M. (2000). *Stop! and Go? - Neuroanatomical correlates and consequences of the inhibition of ongoing responses*. Unpublished doctoral dissertation, University of Marburg, Germany.
- Rieger, M., & Gauggel, S. (1999). Inhibitory after-effects in the stop signal paradigm. *British Journal of Psychology*, 90(4), 509-520.
- Robbins, T. W. (1998). Dissociating executive functions of the prefrontal cortex. In A. C. Roberts, Robbins T.W. & L. Weinberantz (Eds.), *The prefrontal cortex: Executive and cognitive function*. New York: Oxford University Press.
- Roberts, L. E., Rau, H., Lutzenberger, W., & Birbaumer, N. (1994). Mapping P300 waves onto inhibition: Go/no-go discrimination. *Electroencephalography and Clinical Neurophysiology*, 92, 44-55.

- Roberts, R. J. J., & Pennington, B. F. (1996). An interactive framework for examining prefrontal cognitive processes. *Developmental Neuropsychology*, 12(1), 105-126.
- Rockstroh, B., Mueller, M., Cohen, R., & Elbert, T. (1992). Probing the functional brain state during P300-evocation. *Journal of Psychophysiology*, 6, 175-184.
- Rodriguez-Fornells, A., Lorenzo-Seva, U., & Andres-Pueyo, A. (2002). Are high-impulsive and high risk-taking people more motor disinhibited in the presence of incentive? *Personality & Individual Differences*, 32(4), 661-683.
- Rosenthal, R. H., & Allen, T.W. (1978). An examination of attention, arousal, and learning dysfunctions of hyperkinetic children. *Psychological Bulletin*, 85(4), 689-715.
- Ross, R. G., Harris, J. G., Olincy, A., & Radant, A. (2000). Eye movement task measures inhibition and spatial working memory in adults with schizophrenia, ADHD, and a normal comparison group. *Psychiatry Research*, 95(1), 35-42.
- Rowe, J. B., Toni, I., Josephs, O., Frackowiak, R. S. J., & Passingham, R. E. (2000). The prefrontal cortex: Response selection or maintenance within working memory? *Science*, 288, 1656-1660.
- Roy-Byrne, P., Scheele, L., Brinkley, J., Ward, N., Wiatrak, C., Russo, J., Townes, B., & Varley, C. (1997). Adult attention-deficit hyperactivity disorder: Assessment guidelines based on clinical presentation to a specialty clinic. *Comprehensive Psychiatry*, 38(3), 133-140.
- Rubia, K. (2002). The dynamic approach to neurodevelopmental psychiatric disorders: use of fMRI combined with neuropsychology to elucidate the dynamics of psychiatric disorders, exemplified in ADHD and schizophrenia. *Behavioural Brain Research*, 130(1-2), 47-56.
- Rubia, K., Overmeyer, S., Taylor, E., Brammer, M., Williams, S. C., Simmons, A., Andrew, C., & Bullmore, E. T. (2000). Functional frontalisation with age: mapping neurodevelopmental trajectories with fMRI. *Neuroscience & Biobehavioral Reviews*, 24(1), 13-19.
- Rubia, K., Overmeyer, S., Taylor, E., Brammer, M., Williams, S. C., Simmons, A., & Bullmore, E. T. (1999). Hypofrontality in attention deficit hyperactivity disorder during higher-order motor control: a study with functional MRI. *American Journal of Psychiatry*, 156(6), 891-896.

- Rubia, K., Russell, T., Overmeyer, S., Brammer, M. J., Bullmore, E. T., Sharma, T., Simmons, A., Williams, S. C., Giampietro, V., Andrew, C. M., & Taylor, E. (2001). Mapping motor inhibition: conjunctive brain activations across different versions of go/no-go and stop tasks. *Neuroimage*, 13(2), 250-261.
- Rubia, K., Smith, A. B., Brammer, M. J., & Taylor, E. (2003). Right inferior prefrontal cortex mediates response inhibition while mesial prefrontal cortex is responsible for error detection. *NeuroImage*, 20(1), 351-358.
- Ruchkin, D. S., & Glaser, E. M. (1978). Simple digital filters for examining CNV and P300 on a single trial basis. In D. Otto (Ed.), *Multidisciplinary perspectives in event-related brain potential* (pp. 579-581). Washington: U.S. Government Printing Office.
- Sasaki, K., Gemba, H., Nambu, A., & Matsuzaki, R. (1993). No-go activity in the frontal association cortex of human subjects. *Neuroscience Research*, 18(3), 249-252.
- Sasaki, K., Gemba, H., & Tsujimoto, T. (1989). Suppression of visually initiated hand movement by stimulation of the prefrontal cortex in the monkey. *Brain Research*, 495(1), 100-107.
- Schachar, R. (1991). Childhood hyperactivity. *Journal of Child Psychology and Psychiatry*, 32, 155-191.
- Schachar, R., & Logan, G. (1990a). Are hyperactive children deficient in attentional capacity? *Journal of Abnormal Child Psychology*, 18(5), 493-513.
- Schachar, R., & Logan, G. D. (1990b). Impulsivity and inhibitory control in normal development and childhood psychopathology. *Developmental Psychology*, 26(5), 710-720.
- Schachar, R., Mota, V. L., Logan, G. D., Tannock, R., & Klim, P. (2000). Confirmation of an inhibitory control deficit in attention-deficit/hyperactivity disorder. *Journal of Abnormal Child Psychology*, 28(3), 227-235.
- Schachar, R. J., Chen, S., Logan, G. D., Ornstein, T. J., Crosbie, J., Ickowicz, A., & Pakulak, A. (2004). Evidence for an error monitoring deficit in attention deficit hyperactivity disorder. *Journal Abnormal Child Psychology*, 32(3), 285-293.



- Schall, J. D., Stuphorn, V., & Brown, J. W. (2002). Monitoring and control of action by the frontal lobes. *Neuron*, 36(2), 309-322.
- Scheffers, M. K., Coles, M. G. H., Bernstein, P., Gehring, W. J., & Donchin, E. (1996). Event-related brain potentials and error-related processing: An analysis of incorrect responses to go and no-go stimuli. *Psychophysiology*, 33(1), 42-53.
- Scheres, A., Oosterlaan, J., & Sergeant, J.A. (2001). Response execution and inhibition in children with AD/HD and other disruptive disorders: The role of behavioural activation. *Journal of Child Psychology and Psychiatry*, 42(3), 347-357.
- Schröger, E. (1993). Event-related potentials to auditory stimuli following transient shifts of spatial attention in a Go/Nogo task. *Biological Psychology*, 36, 183-207.
- Schwarzenau, P., Falkenstein, M., Hoorman, P., & Hohnsbein, J. (1998). A new method for the estimation of the onset of lateralized readiness potential (LRP). *Behavior Research Methods, Instruments, & Computers*, 30(1), 110-117.
- Schweitzer, J. B., Lee, D. O., Hanford, R. B., Zink, C. F., Ely, T. D., Tagamets, M. A., Hoffman, J. M., Grafton, S. T., & Kilts, C. D. (2004). Effect of methylphenidate on executive functioning in adults with attention-deficit/hyperactivity disorder: Normalization of behavior but not related brain activity. *Biological Psychiatry*, 56(8), 597-606.
- Segalowitz, S. J. (2000). Dynamics and variability of brain activation: Searching for neural correlates of skill acquisition. *Brain & Cognition*, 42(1), 163-165.
- Semlitsch, H. V., Anderer, P., Schuster, P., & Presslich, O. (1986). A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology*, 23(6), 695-703.
- Sergeant, J. (2000). The cognitive-energetic model: An empirical approach to attention-deficit hyperactivity disorder. *Neuroscience and Behavioural Reviews*, 24, 7-12.
- Sergeant, J. A., & van der Meere, J.J. (1990). Converging approaches on localizing the hyperactivity deficit. In B. B. Lahey, & Kazdin, A.E. (Ed.), *Advances in clinical child psychology* (Vol. 13, pp. 207-245). New York: Plenum Press.

- Sergeant, J. A., Guerts, H., Huijbregts, S., Scheres, A., & Oosterlaan, J. (2003). The top and bottom of ADHD: a neuropsychological perspective. *Neuroscience and Biobehavioral Reviews*, 27, 583-592.
- Sergeant, J. A., Oosterlaan, J., & Van der Meere, J. (1999). Information processing and energetic factors in attention-deficit/hyperactivity disorder. In H. C. Q. A. E. Hogan (Ed.), *Handbook of disruptive behaviour disorders* (pp. 75-104). New York: Plenum Press.
- Shallice, T., & Burgess, P. (1991). Higher-order cognitive impairments and frontal lobe lesions in man. In H. Levin, H. Eisenberg & B. A. (Eds.), *Frontal lobe function and dysfunction* (pp. 125-138). New York: Oxford University Press.
- Simson, R., Vaughan, H. G. J., & Ritter, W. (1977). The scalp topography of potentials in auditory and visual go-nogo tasks. *Electroencephalography and Clinical Neurophysiology*, 43, 864-875.
- Smid, H., Fiedler, R., & Heinze, H. J. (2000). An electrophysiological study of the insertion of overt response choice. *Journal of Experimental Psychology: Human Perception & Performance*, 26(3), 1053-1071.
- Smith, L. (1952). *A dictionary of psychiatry for the layman*. London: Maxwell.
- Smulders, F. T. Y., Kenemans, J. L., & Kok, A. (1996). Effects of task variables on measures of the mean onset latency of LRP depend on the scoring method. *Psychophysiology*, 33, 194-205.
- Snyder, E., & Hillyard, S. A. (1976). Long latency evoked potentials to irrelevant, deviant stimuli. *Behavioural Biology*, 16, 319-331.
- Solanto, M. V. (2002). Dopamine dysfunction in AD/HD: Integrating clinical and basic neuroscience research. *Behavioural Brain Research*, 130, 65-71.
- Sonuga-Barke, E. J. S. (1998). Categorical models of childhood disorder: A conceptual and empirical analysis. *Journal of Child Psychology and Psychiatry*, 39(1), 115-133.
- Sonuga-Barke, E. J. S., Taylor, E., Sembi, S., & Smith, J. (1992). Hyperactivity and delay aversion-I. The effect of delay choice. *Journal of Child Psychology and Psychiatry*, 33(1), 387-398.

- Soubrie, P. (1986). Reconciling the role of central serotonin neurons in human and animal behaviour. *Behavioural Brain Science*, 9, 319-364.
- Spencer, K. M., Dien, J., & Donchin, E. (2001). Spatiotemporal analysis of the late ERP responses to deviant stimuli. *Psychophysiology*, 38, 343-358.
- Spencer, T., Biederman, J., Wilens, T. E., & Faraone, S. V. (2002). Overview and neurobiology of Attention-deficit/Hyperactivity Disorder. *Journal of Clinical Psychiatry*, 63, 3-9.
- Squires, K., Petuchowski, S., Wickens, C., & Donchin, E. (1977). The effects of stimulus sequence on event related potentials: A comparison of visual and auditory sequences. *Perception & Psychophysics*, 22(1), 31-40.
- Squires, K. C., Wickens, C., Squires, N. K., & Donchin, E. (1976). The effect of stimulus sequence on the waveform of the cortical event-related potential. *Science*, 193(4258), 1142-1146.
- Squires, N. K., Squire, K. C., & Hillyard, S. A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and Clinical Neurophysiology*, 38, 387-401.
- Stadler, C., & Janke, W. (2003). Concurrent validity of the German version of S.B. Eysenck's impulsiveness questionnaire for children. *Personality and Individual Differences*, 35(1), 51-58.
- Stout, J. C., Wyman, M. F., Johnson, S. A., Peavy, G. M., & Salmon, D. P. (2003). Frontal behavioural syndromes and functional status in probable Alzheimer disease. *American Journal of Geriatric Psychiatry*, 11(4), 1-4.
- Strik, W. K., Fallgatter, A. J., Brandeis, D., & Pascual-Marqui, R. D. (1998). Three-dimensional tomography of event-related potentials during response inhibition: Evidence for phasic frontal lobe activation. *Electroencephalography & Clinical Neurophysiology*, 108, 406-413.
- Stuss, D. T., Levine, B., Alexander, M. P., Hong, J., Palumbo, C., Hamer, L., Murphy, K. J., & Izukawa, D. (2000). Wisconsin card sorting test performance in patients with focal frontal and posterior brain damage: effects of lesion location and test structure on separable cognitive processes. *Neuropsychologia*, 38, 388-402.

- Swainson, R., Cunnington, R., Jackson, G. M., Rorden, C., Peters, A. M., Morris, P. G., & Jackson, S. R. (2003). Cognitive control mechanisms revealed by ERP and fMRI: Evidence from repeated task-switching. *Journal of Cognitive Neuroscience*, 15(6), 785-799.
- Tabachnick, B. G., & Fidell, L. S. (1989). *Using multivariate statistics*. New York: HarperCollins.
- Tannock, R. (1998). Attention deficit hyperactivity disorder: Advances in cognitive, neurobiological, and genetic research. *Journal of Child Psychology & Psychiatry & Allied Disciplines*, 39(1), 65-99.
- Tannock, R., Schachar, R., & Logan, G. (1995). Methylphenidate and cognitive flexibility: Dissociated dose effects in hyperactive children. *Journal of Abnormal Child Psychology*, 23(2), 235-266.
- Tannock, R., Schachar, R. J., Carr, R. P., Chajczyk, D., & Logan, G. D. (1989). Effects of methylphenidate on inhibitory control in hyperactive children. *Journal of Abnormal Child Psychology*, 17, 473-491.
- Tekok-Kilic, A., Shucard, J.L., & Shucard, D.W. (2001). Stimulus modality and go/nogo effects on P3 during parallel visual and auditory continuous performance tasks. *Psychophysiology*, 38, 578-589.
- Turner, D. C., Clark, L., Dowson, J., Robbins, T. W., & Sahakian, B. J. (2004). Modafinil improves cognition and response inhibition in adult attention-deficit/hyperactivity disorder. *Biological Psychiatry*, 55(10), 1031-1040.
- Turner, D. C., Robbins, T. W., Clark, L., Aron, A. R., Dowson, J., & Sahakian, B. J. (2003). Cognitive enhancing effects of modafinil in healthy volunteers. *Psychopharmacology*, 165(3), 260-269.
- van Boxtel, G. J., van der Molen, M. W., Jennings, J. R., & Brunia, C. H. (2001). A psychophysiological analysis of inhibitory motor control in the stop-signal paradigm. *Biological Psychology*, 58(3), 229-262.
- van Boxtel, G. J. M. (1998). Computational and statistical methods for analyzing event-related potential data. *Behavior Research Methods, Instruments, & Computers*, 30(1), 87-102.

- van Boxtel, G. J. M. (2003). The use of the subtraction technique in the psychophysiology of response inhibition and conflict. In M. Ullsperger, & M. Falkenstein (Eds.), *Errors, conflicts, and the brain: Current opinions on performance monitoring* (pp. 219 - 225). Leipzig: MPI cognitive neuroscience.
- van Boxtel, G. J. M., & Band, G. P. H. (2000). Inhibitory motor control in stop paradigms: Reply to McGarry and Franks (2000). *Acta Psychologica*, 105, 79-82.
- Van den Wildenberg, W. P. M. (2003). *Perspectives on stopping behavior: Process analyses of stop-signal inhibition*. Unpublished doctoral dissertation, University of Amsterdam, Netherlands.
- van den Wildenberg, W. P. M., van Boxtel, G. J. M., & van der Molen, M. W. (2003). The duration of response inhibition in the stop-signal paradigm varies with response force. *Acta Psychologica*, 114(2), 115-129.
- van den Wildenberg, W. P. M., & van der Molen, M. W. (2004a). Additive factors analysis of inhibitory processing in the stop-signal paradigm. *Brain and Cognition*, 56(2), 253-266.
- van den Wildenberg, W. P. M., & van der Molen, M. W. (2004b). Developmental trends in simple and selective inhibition of compatible and incompatible responses. *Journal of Experimental Child Psychology*, 87(3), 201-220.
- van den Wildenberg, W. P. M., van der Molen, M. W., & Logan, G. D. (2002). Reduced response readiness delays stop signal inhibition. *Acta Psychologica*, 111(2), 155-169.
- van der Meere, J., & Sergeant, J. (1988). Controlled processing and vigilance in hyperactivity: Time will tell. *Journal of Abnormal Child Psychology*, 16, 641-656.
- van der Molen, W. M. (2000). Developmental changes in inhibitory processing: Evidence from psychophysiological measures. *Biological Psychology*, 54(1-3), 207-239.
- van der Schoot, M., Licht, R., Horsley, T. M., & Sergeant, J. A. (2002). Fronto-central dysfunctions in reading disability depend on sub-type: guessers but not spellers. *Developmental Neuropsychology*, 22(3), 533-564.

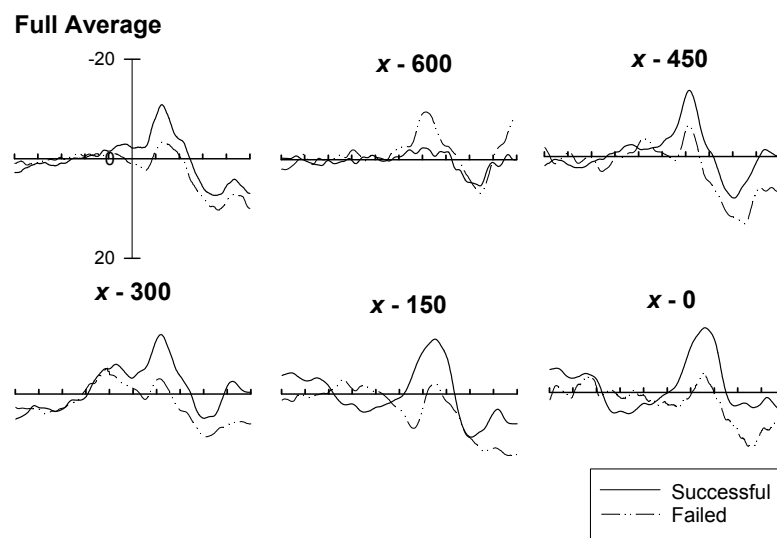
- Van Veen, V., & Carter, C. S. (2002). The anterior cingulate as a conflict monitor: fMRI and ERP studies. *Physiology & Behavior*, 77(4-5), 477-482.
- van Veen, V., & Carter, C. S. (2002). The timing of action-monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience*, 14(4), 593-602.
- Vaughan, H. G. J., & Ritter, W. (1970). The sources of auditory evoked responses recorded from the human scalp. *Electroencephalography & Clinical Neurophysiology*, 28, 360-367.
- Verbruggen, F., Liefvooghe, B., & Vandierendonck, A. (2004). The interaction between stop signal inhibition and distractor interference in the flanker and Stroop task. *Acta Psychologica*, 116(1), 21-37.
- Vigil-Colet, A., & Codorniu-Raga, M. J. (2004). Aggression and inhibition deficits, the role of functional and dysfunctional impulsivity. *Personality and Individual Differences*, 37(7), 1431-1440.
- Waldman, I. D., Rowe, D. C., Abramowitz, A., Kozel, S. T., Mohr, J. H., Sherman, S. L., Cleveland, H. H., Sanders, M. L., & Stever, C. (1998). Association and linkage of the dopamine transporter gene (DAT1) and Attention Deficit Hyperactivity Disorder in children. *American Journal of Human Genetics*, 63, 1767-1776.
- Ward, M. F., Wender, P. H., & Reimherr, F. W. (1993). The Wender Utah rating Scale: An aid in the retrospective diagnosis of childhood attention deficit-hyperactivity disorder. *American Journal of Psychiatry*, 150, 885-890.
- Weis, G., & Hechtman, L. (1986). *Hyperactive children growing up*. New York: Guilford Press.
- Wender, P. H., Wolf, L. E., & Wassertein, J. (2001). Adults with ADHD: An overview. *Annals of the New York Academy of Sciences*, 931, 1-16.
- Weyandt, L. L., & Willis, W. G. (1994). Executive functions in school-aged children: potential efficacy of tasks in discriminating clinical groups. *Developmental Neuropsychology*, 19, 27-38.

- White, H. K., Moffitt, T. E., Caspi, A., Bartusch, D. J., Needles, D. J., & Stouthamer-Loeber, M. (1994). Measuring impulsivity and examining its relationship to delinquency. *Journal of Abnormal Psychology, 103*, 192-205.
- Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental Psychology, 35*(1), 205-213.
- Winstanley, C. A., Dalley, J. W., Theobald, D. E., & Robbins, T. W. (2004). Fractionating impulsivity: Contrasting effects of central 5-HT depletion on different measures of impulsive behavior. *Neuropsychopharmacology, 29*(7), 1331-1343.
- Wodushek, T. R., & Neumann, C. S. (2003). Inhibitory capacity in adults with symptoms of Attention Deficit/Hyperactivity Disorder (ADHD). *Archives of Clinical Neuropsychology, 18*(3), 317-330.
- Woldorff, M. G. (1993). Distortion of ERP averages due to overlap from temporal adjacent ERPs: Analysis and correction. *Psychophysiology, 30*, 98-119.
- Wolf, L. E., & Wassertein, J. (2001). Adults ADHD: Concluding thoughts. *Annals of the New York Academy of Sciences, 931*, 396-408.
- Zametkin, A. J., & Rapoport, J. L. (1987). Noradrenergic hypothesis of attention deficit disorder with hyperactivity: A critical review. In H. Y. Meltzer (Ed.), *Pharmacology: The third generation of progress* (pp. 837-842). New York: Raven Press.
- Zaparniuk, J., & Taylor, S. (1997). Impulsivity in children and adolescents. In C. D. Webster & M. A. Jackson (Eds.), *Impulsivity: Theory, assessment, and treatment* (pp. 158-179). New York: The Guilford Press.
- Zuckerman, M. (1993). Sensation seeking and impulsivity: A marriage of traits made in biology? In W. G. McCown, J. L. Johnson & M. B. Shure (Eds.), *The impulsive client: Theory, research, and treatment* (pp. 71-91). Washington, DC: American Psychological Association.
- Zuckerman, M. (2002). Personality and psychopathy: Shared behavioral and biological traits. In J. Glicksohn (Ed.), *The neurobiology of criminal behavior neurobiological foundation of aberrant behaviors* (pp. 27-49). Dordrecht, Netherlands: Kluwer Academic Publishers.

## **Appendices**

### **Appendix A: Correction of ERP Overlap**

As can be seen in Figure 1, the correction procedure reduced activity preceding the stop-signal, resulting in similar and flatter baseline activity for successful and failed stop trials in the “Full Average” waveform.<sup>44</sup>



**Figure 1.** ERP group average waveforms at each stop-signal delay and the “Full Average” waveform across delays at the Cz site. Notes: (1) *x*-axis ticks = 100 ms, (2) *y*-axis =  $\pm 20 \mu\text{V}$ , (3) vertical bar indicates stop-signal onset.

### **Appendix B: A Comparison of LRP Onset Estimation Methods**

The onset of the LRP was examined using two procedures: the 1df subtype of the segmented regression procedure (Schwarzenau, Falkenstein, Hoorman, Hohnsbein, 1998)

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<sup>44</sup> Data from the simple stop-signal task in Study I (Chapter 4) was used to calculate the ERP waveforms ( $n = 29$ ).



and the criterion procedure (Osman & Moorer, 1993). Table 1 shows the mean difference in LRP onsets between conditions for each trial type and each procedure, and the statistical analyses for the Condition (rare stop-signal probability versus frequent stop-signal probability) by Procedure (regression versus criterion) interactions. The two procedures did not differ significantly, strengthening the validity of the LRP findings in Study IV (Chapter 7).

**Table 1. The mean difference in the estimated onset of stimulus and response-locked LRPs and the statistical analyses reflecting the Condition x Procedure interactions.**

	Regression (ms)	Criterion (ms)	<i>F</i>	<i>p</i>
<b><u>Stimulus-locked LRP onset</u></b>				
Successful-stops	19.5	16.2	0.1	.706
Failed-stops	84.5	70.2	1.7	.206
Ignore-signals	7.8	15.5	1.6	.210
No-signals	14.2	16.2	.06	.815
<b><u>Response-locked LRP onset</u></b>				
Failed-stops	48.4	36.6	3.0	.092
Ignore-signals	9.7	4.6	0.8	.393
No-signals	59.1	67.0	0.3	.586

## Appendix C: SPSS Output and Electronic Documents

The rest of the appendix for this thesis is in electronic form as inclusion in hardcopy was impractical. The enclosed CD contains: (a) relevant SPSS output (in Microsoft Word format) for performance, psychometric and ERP measures, and (b) documents used in initial contacts with subjects and in experimental sessions. For information on viewing these files see “readme.txt” on the CD.